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MEASUREMENT AND ANALYSIS OF IGNITION INTERFERENCE — 150 KC TO 10 KMC

WILLIAM K. HARTELL
and
VICTOR PODBIELSKI

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MEASUREMENT AND ANALYSIS

OF

IGNITION INTERFERENCE - 150 KC to 10 KMC

* * * * *

William K. Hartell

and

Victor Podbielski

MEASUREMENT AND ANALYSIS

OF

IGNITION INTERFERENCE - 150 KC to 10 KMC

by

William K Hartell

Lieutenant, United States Navy

and

Victor Podbielski

Lieutenant Junior Grade, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

United States Naval Postgraduate School
Monterey, California

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ABSTRACT

Interference problems have become increasingly important in insuring reliable communications and proper functioning of other electronic systems Ignition system radiation is one of the common man-made sources of radio frequency interference.

Previous work in measurement and analysis of ignition radiation is summarized. Results are given for screen room measurements of a mock-up ignition system over the frequency range of 150 kc to 10 kmc. Resistive high-tension leads are compared with regular low resistance ignition leads. Measurements were also made on a 1962 model car over the same frequency range and are compared with a proposed International Limit for ignition interference. Waveforms of current flow through one spark plug and spectrum analyzer displays of radiation are shown and discussed. Recommendations are made for ignition interference limits.

The writers wish to express their appreciation for the assistance given them by Professor P. E. Cooper, Associate Professor D. A. Stentz, and Lieutenant R. L. Browning in this investigation.

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1. Introduction

Our general interest in interference problems and man-made radio noise sources was narrowed down to ignition interference by several factors. One was the remarks of E. W. Allen, Federal Communication Commission, in a paper published as part of a book of talks given at the conference on Radio Noise, held at Harvard College Observatory, April, 1958. (24) A part of his remarks are quoted here:

> As far as I am aware, there are no recent measurements of the levels of ignition noise to be found in populous areas. Quantitive measurements on frequencies between 40 and 450 mc were made back in 1940 by R. W. George, but these are likely to be no longer valid because of changes in automobile design and of the factors to which I have referred above. (Use of various suppression methods such as resistive leads).

In addition other references on automobile ignition systems were written either in the 1940's or have been done by various European groups since then. These studies were limited to approximately 30 to 600 mc and included little recent data on waveforms or the frequency spectrum of the ignition spark.

As our world becomes more electronic minded and depends on many automatic electronic devices the problems of noise and interference are brought into focus as serious limitations on many systems. D. H. Menzel has said: (24)

> This modern era has had many names: the golden age, the machine age, the atomic age, the electronic age, and so on. One further title, hitherto unpublicized, it eminently deserves: the age of noise. Man has compounded the natural noise that preceded his existence on the earth until no point on this globe is free from it. Even in the desert's

hush, radio waves pervade the air and provide a source of potential noise.

It is hoped that this paper will serve some purpose in its attempt to summarize the important past work in the ignition interference field, by extension of the limits of frequencies measured, photographs showing characteristics of the spark breakdown and resulting oscillations, and photographs of the radiation intensity versus frequency on the spectrum analyzer.

Ignition system radiation is only one of the many sources of radio frequency interference However it is an important factor and limitation in many applications. The study of ignition interference also has broader applications in that it is a part of a general class of noise or interference referred to as "impulse noise".

Section two will briefly review the general problem of radio interference and its reduction or suppression The basic source of ignition radiation and its effects are also described. The following sections will give results of measurements of ignition radiation and the various standards and limits which now apply or are proposed. Recommendations for extending these limits and areas of additional work are made in Section 9.

2 Radio Interference Reduction and Spectrum Utilization

We are rapidly reaching a stage in our electronic and communication systems development where the radio frequency spectrum is becoming overcrowded. This includes desired and undesired signals in addition to the many sources of noise and interference. In the early years of communication equipment, design was carried out in relative noiseless environment to the extent that there was usually plenty of frequency spectrum to work in or move to if one particular section became overcrowded. Also many of the man-made interference sources were not present at that time. For many years this approach of changing to a new frequency band was adequate. However, as the frequency spectrum became crowded the various electronic systems tried to adapt themselves to the increased interference or noise levels by several methods.

1. Accepting the increased noise.
2. Moving to less used frequency bands.
3. Using frequency allocation plans.
4. Setting power limitations on radiated power.
5. Time-sharing of certain frequencies.
6. Moving receivers to sites which have low ambient levels.
7. Reducing the interference source
8. Designing the signal to overcome the interference
9. Using directional antennas.
10. Reducing bandwidth requirements of each channel.

Conservation of the radio frequency spectrum and reduction of radio interference are not always possible at the same time in a present day electronic system facility. Spectrum conservation means the minimum utilization of radio frequencies, while operation of the system to meet interference-free criteria may require many radio frequencies and even duplication to meet operational standards. In many systems a certain amount of interference is tolerable and therefore for optimum utilization of the radio frequency spectrum some interference level must be designed into the system as an acceptable limit.

Since much of the interference is man-made, it would seem that it would be subject to control. However, many factors have prevented this, such as constant production of new equipment which may be noise sources, unawareness of interference problems by many people in the design and production field, and the most difficult perhaps is the unidentified sources which remain anonymous and continue to radiate interfering signals or noise. Much of the opposition to the various methods and techniques for reduction of interference has been based on some of the following disadvantages:

1. Increased cost of the system.
2. Delays in production if held up for changes to meet interference criteria.
3. Increased weight and complexity of the system.
4. Short duration and infrequency of occurrence of some types of interference.

5. Change in system performance if interference methods or components are introduced into the system.

This neglect or opposition to incorporating interference design or criteria has been possible, to some extent, because of the human element or operator being somewhere in the communication path acting as a filter to prevent action on inaccurate data. However, at present there is more and more action taken or information transmitted without any human filter or evaluation. This means that more emphasis must be placed on interference reduction to prevent errors in various electronic systems.

For the proper operation of an electronic system one of the primary factors is the reception of a signal which is strong enough to be discernable and correctly interpreted in the presence of any interference signal or noise which it may encounter before reaching the termination of its path. Some of the basic sources which it may have to overcome are:

1. Interference from man-made sources.
2. Atmospheric discharges.
3. Receiver noise.
4. Thermal noise.
5. Various cosmic radiations.

Ignition systems for internal combustion engines, oil burners, and other similar devices are prolific sources of radiated and conducted interference. They produce pulses of energy capable of interfering with radio reception at most frequencies in current use. One of the main characteristics of impulse noise is the fact that the noise energy is initially deliver-

ed in very intense bursts of very short duration. Therefore the fraction-of-time envelope distribution of the noise energy is affected by the frequency characteristics of the receiver or filter. The time interval over which the noise power is average has a definite effect on the percentage-of-time distribution of the noise power (20).

Arcing is produced in the primary or low-tension side of an ignition system by the contact-breaker points and in the high-tension system by the distributor gap and spark plug. Further arcing may occur if the ignition leads or other components are defective. Voltages produced by such sparking and arcing inherently have steep wavefronts and as such contain many high order harmonics of the fundamental frequency, causing oscillations of relatively high frequencies that may develop large amplitudes if resonant conditions exist. These may radiate directly from the arc, from primary leads, from secondary or high-tension leads, or from any metallic objects not bonded and grounded. In addition, the physical layout of the system is such as to offer a very favorable radiation system. The lengths of wire between the distributor and the spark plugs become very effective antennas at wavelengths shorter than about ten times the length of the lead (11). Further, the various disposition of the wires and other system components serving as antennas assures polarization in all planes.

The large frequency range of the radiation from an ignition system classifies it as a wideband transmitter and, therefore, a serious source of electromagnetic interference. Because of its large frequency range and erratic occurrence, it is very difficult and costly to obtain complete

suppression of the interference over the entire spectrum.

A study of ignition systems is important not only for the interference they cause but they are producers of interference similar to many devices which have switching transients. Switching transients result from the make or break of an electric current and are extremely sharp impulses. Their duration and peak value depends upon the current intensity and nature of the circuit being opened or closed. Their effect is to cause sharp clicks in audio outputs or receivers and sharp spikes or points on oscillo-scope traces. The isolated occasional occurrence of a switching transient may have little significance depending on the system affected. However, if repeated often enough and with sufficient regularity, switching transients are capable of creating intolerable interference or even malperformance. Typical sources of sustained regularly recurring switching transients are commutators of d-c motors and generators, navigational pulsed lights, continuous wave key clicks, and some electronic switching circuits.

3. Ignition System and Spark Discharge.

The typical system consists of two circuits designated as the primary circuit (low-tension) and the secondary circuit (high-tension). The primary circuit consists of the battery, the ignition switch, the primary winding of the ignition coil, the breaker contacts, and the condenser. The secondary circuit consists of the secondary winding of the ignition coil, the distributor, the high tension leads, and the spark plugs. The closing and opening of the breaker contacts controls the starting and stopping of the flow of current in the primary circuit, which creates and collapses a magnetic field in the ignition coil. The variation in the magnetic field induces a voltage in the secondary winding of the coil according to the basic formula: $e = n \, d\Phi/dt$. The collapse of the magnetic field is more rapid than its establishment. The combination of a rapid collapse and a large number of secondary coil turns is sufficient to create a voltage which will produce a spark at the spark plug gap. The distributor acts as a rotating switch, which "distributes" the high voltage produced in the secondary winding to the right spark plug at the correct time. This gap in the distributor also produces spark discharges which have transients currents that affect the interference radiation. The magnitude of the voltage generated in the secondary winding of the coil depends on several factors such as the strength of the magnetic field, the speed of the collapses, the efficiency of the electro-magnetic coupling between the primary and secondary and number of coil turns. In theory the secondary voltage could be built up at an infinite rate but the physical constants of the system give a finite rate of

voltage rise. This voltage rise can be very rapid but is in itself not a serious cause of interference (11). The greatest interference is the result of the almost instantaneous current surge after the voltage breakdown of the spark gap. Large amounts of power are generated in this process and estimates of the average power output of an ignition system go up to 20 watts. However only a small portion of this is converted to radio energy. In addition the power is distributed over a very large frequency spectrum with varying efficiencies of radiation from the system. Therefore the resulting energy in any narrow frequency band will be small.

The rapid discharge of current through the spark gap will set up an electromagnetic shock wave which will radiate from the system. This shock wave or very narrow intense impulse will establish oscillations in any resonant circuit in which it is received. The frequency of the oscillation will depend on the parameters of the received circuit. These oscillations will be detected by the receiver and amplified. If the spark discharge takes place in a circuit which has resonant conditions then these will also produce damped oscillations which will radiate or modulate the higher frequency components. The ignition system has many resonances and therefore the resulting radiation will be a complex wave with interaction between the various components. As stated by Nethercot (13) the ignition leads from the distributor to the coil and the spark plugs can be considered as transmission lines that are grossly mismatched as to the proper terminating impedance. This mismatch causes reflections and damped oscillations. These oscillations and times for reflections are a function of the electrical

length of the ignition leads; therefore measureable differences of radiation should exist between ignition systems with various lengths of cable.

The average eight cylinder automobile engine produces approximately 3,000 revolutions per mile (25). Four sparks are required per revolution, therefore in one mile 12,000 sparks will occur. If the automobile is traveling at 40 miles per hour it will cover this distance in 1-1/2 minutes. Sparks will occur at the rate of 8,000 per minute, or 133 per second.

Thus the ignition system is a very important source of impulsive interference with its broadband frequency characteristics and repetition rates of approximately 100 to 150 pulses per second. The problem of suppression of the radiation from the ignition system has been discussed and worked on by many investigators (11, 12, 16, 18, 26). Most of this work has been in the same frequency range as previous measurements have been made - 40 to 650 mc. The various methods which have been tried are:

1. Distributed resistive leads.
2. Lumped resistors at the spark plugs or distributor.
3. Capacitors and inductors at various points in the system.
4. Resistive spark plugs.
5. Shielding of components
6. Various combinations of the above.

For normal usage on most vehicles resistive leads have been successful in reducing the interference to car radios. For some special requirements and for military use around an electronic facility complete shielding is used. A typical example of a complete shielding arrangement for a gasoline

engine at a military installation is shown in Fig 1. The filters in the lay-out are used to prevent the interference being conducted to the low voltage circuit by way of the battery (21).

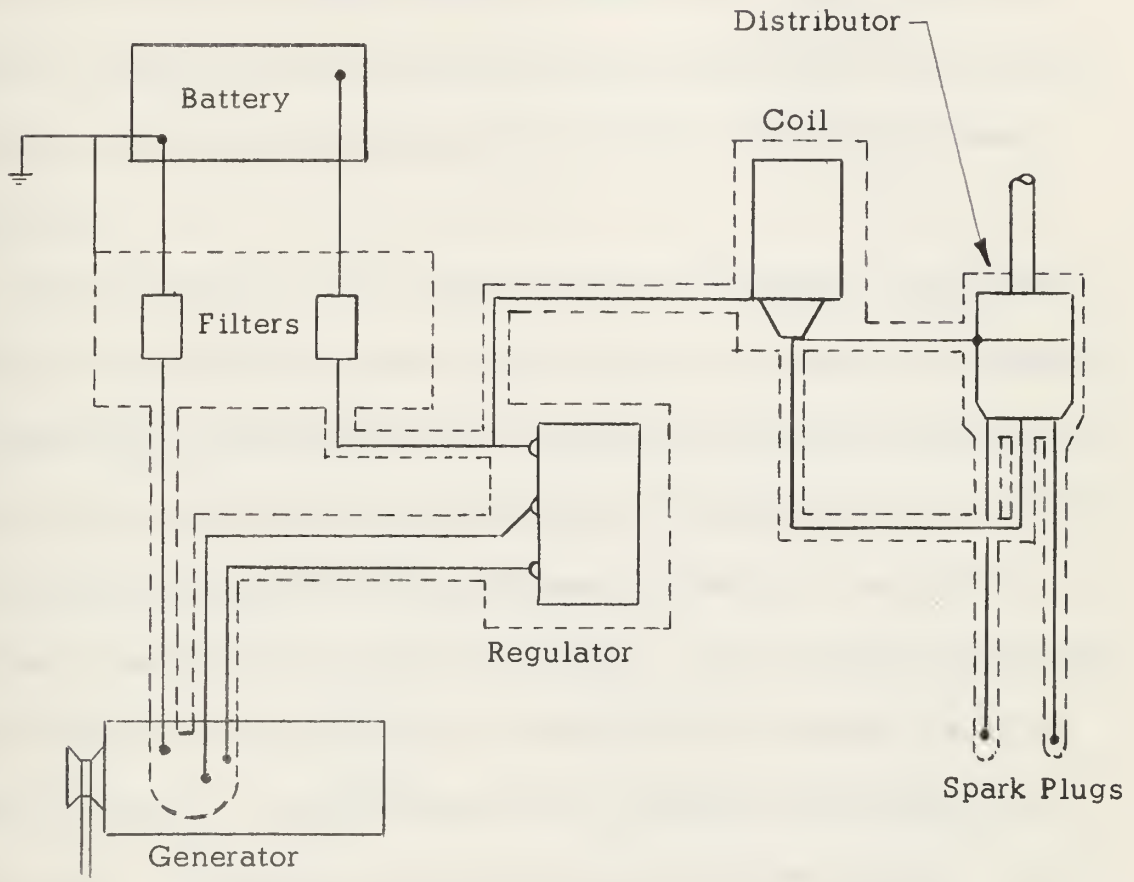


Fig. 1. Shielded Ignition System.

This shielding must be effective over the frequency range of 14 kc to 1000 mc and be reliable in service after years of use. Specification MIL-I-16165C (SHIPS) provides for such shielding. Recalling that the maximum interference from the ignition system is in the higher frequency ranges and that joint leakage increases with frequency, it becomes apparent that the problem of joints in shielding is far more serious than the leakage due to

penetration. This is further aggravated by the fact that the shielding conduits becomes fairly efficient radiator at very high frequencies, once exterior surface currents have been set up. It is, therefore, of utmost importance that joints be made completely tight and in such a manner that they will remain so for a long time with proper maintenance. One of the problems is bowing of bolted flanges and thermal effects of the metal shielding.

The main function of the ignition system is to produce a spark discharge in the cylinder to ignite the gas mixture. An electrical discharge or spark across a small gap is built up mainly by electron collisions producing fresh ions and electrons in Townsend avalanches. This proceeds as a transient discharge until a maintenance mechanism is established or the energy supplying the spark is dissipated. As the potential difference is increased across a spark gap a voltage is reached where a "sparking condition" exists. A current giving rise to luminous effects falls to a small value. The sparking potential depends on several factors, such as:

1. The distance between the electrodes (spark length).
2. The nature of the gas in the gap
3. The gas pressure.

The time which elapses between the instant of application of a voltage sufficient to cause breakdown across a gap and the occurrence of breakdown is known as the time lag, and consists of two separate parts:

a. The statistical time lag caused by the need for an electron to appear in the gap during the period of application of the voltage in order to

initiate the discharge.

b. The formative time lag corresponding to the time required for the discharge, once it has been initiated, to develop across the gap.

Figure 2 illustrates the observed growth of the spark in air across a 0.5 cm gap. A positive streamer is found to grow across the gap from the anode to meet a small discharge at the cathode. The speed of growth of the positive streamer is approximately 5×10^7 cm/sec. The growth of sparks across gaps of 0.1 to 1.0 cm in air at pressures between 760 and 200 mm Hg. has been investigated by Dunnington[1] who finds that changes occur in the breakdown mechanism with variation in gap length and gas pressure. Breakdown in other gases at various pressures and gap lengths is reviewed in a book by Meek and Craggs (23).

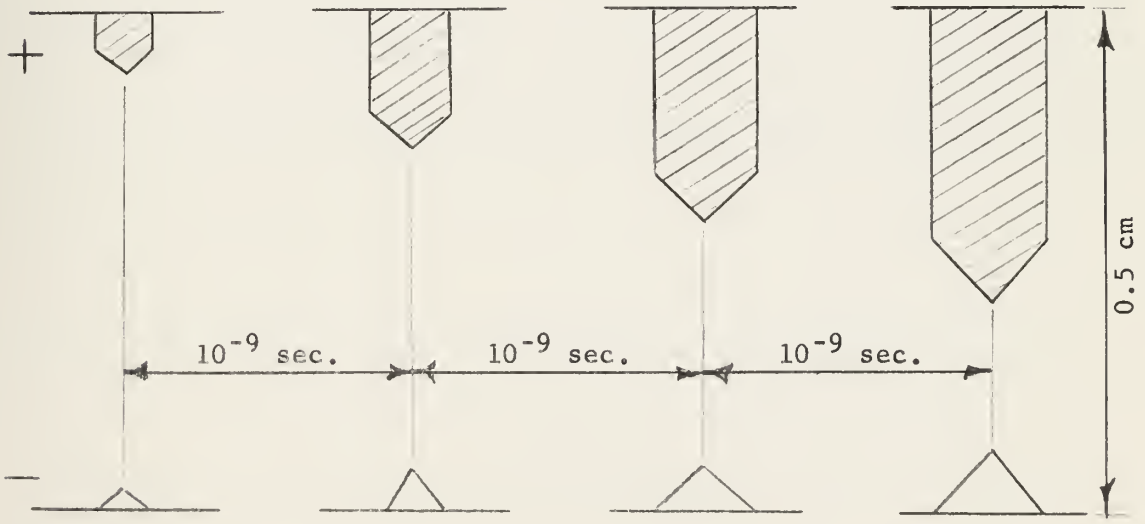


Fig. 2. Growth of a Spark in air across 0.5 cm gap with time intervals of 10^{-9} seconds

[1]Dunnington, Physic Review, Vol. 38, p. 1506, 1931.

Dry air at atmospheric pressures requires about 76 kilovolts to cause a spark between electrodes spaced one inch apart. Since the spark plug electrodes in an automobile system are commonly spaced 0.030 to 0.032 inches apart, about 2300 to 2400 volts would be required to produce a spark between them. The required voltage is actually higher than this because of the compression of the gas-air mixture in the cylinder. In some systems the voltage required may be as high as 8000 volts.

Based on a gap of 0.030 inches or 0.0762 cm and a speed of growth of the spark across the gap of 5×10^{7} cm/sec., a time of about 1.5×10^{-9} seconds is required for the spark to be formed after voltage is applied assuming no statistical time lag.

4. Survey of Ignition Interference Literature

A review of the available papers on the various aspects of ignition interference reveals that much of the more recent work has been done in the European countries. The results of this work may therefore not be readily available in this country. E. W. Allen in a statement previously quoted (24) stated that no recent measurements of ignition noise levels had been made in this country since 1940. However there have been measurements made in several European countries since that time. Most of these have been confined to a relatively small frequency band and were on European model cars To outline the work that has been done in the past and the conclusions that were reached, brief summaries of the previous work are given in this section. Papers which were not reviewed because of similarity to other works or because they were not available may be found listed in the bibliography Some of the theories and conclusions stated in the papers have been changed since the time of their publication.

"Electrical character of the spark discharge of automotive ignition systems," M. F. Peters, G F. Blackburn, and P. T. Hannen, Journal of Research of the National Bureau of Standards, vol 19, research paper RP1032, October 1937.

Summary: To determine the character of a spark discharge, it is necessary to determine current and voltage as functions of time. The measurement of these quantities is facilitated by the use of the cathode-ray

oscillograph, but due consideration must be given to the effect of the measuring circuit, including connections to the oscillograph, on the character of the discharge.

Three methods suitable for measuring the current in the discharge with the cathode-ray oscillograph are 1) measurement of the voltage across a known inductance, 2) measurement of the voltage developed across a current sampling resistor, and 3) deflection of the cathode beam by the magnetic field set up by the current. An analysis is made of oscillograms obtained by these methods for the discharge in a typical ignition circuit. Crest currents of 50 to 80 amps were measured. The frequencies ranged from 6 to 10 mc, the decrement (damping) from 0.08 to 0.40, and energy expended from 0.0023 to 0.0135 joules. The expended energy is found to agree with the energy known to be stored in the capacitance of the circuit at the beginning of the discharge. The breakdown voltage could be calculated from the total energy and capacitance of the system. One value obtained was 11,000 volts for CO_2 gas at 105 psi.

The sources of accidental error in making current or voltage measurements lie chiefly in the measurements of deflection and in determining the sensitivity of the oscillograph. The uncertainty of the values for voltage and current from measurements made on the oscillograms is difficult to determine, especially when the cathode beam is deflected so rapidly that no well-defined trace is left on the film.

Energy was found to be dissipated at the rate of 60 kw at 6.5 mc. It is also probable that there are present in the discharge, especially at

its beginning, still more powerful transient phenomena, of speed too high to be recorded by the oscillograph. In particular the discharge of the capacitance of the spark plug through the low inductance of the spindle shank may give rise to exceedingly high currents of very short duration. For example, the inductance of the spindle shank of a typical mica spark plug computed from its dimensions is about 0.04 uh, and the measured capacitance ranges from 15 uuf for unshielded plugs to 50 uuf for shielded plugs. Using these values, the natural frequency of the discharge of the plug itself would range from 100 to 200 mc and the crest currents for an initial voltage of 5,000 volts would range from 100 to 175 amps. Radiation at these frequencies, as well as at a lower frequency, say 6 mc, of the main capacitive part of the ignition discharge, might cause interference with radio reception. The spark occurring in the secondary circuit of a spark generator on interruption of the primary current usually consists of a number of separate discharges, each of which may consist of a capacitive and an inductive component. In each discharge the decay of the current in the inductive component, if such a component is present, is followed by the rapid rise of resistance of the gap, whereupon the capacitance is again charged to such voltage that the discharge is repeated. The spark ends when there is no longer sufficient energy in the secondary winding to charge the capacitance to the breakdown voltage.

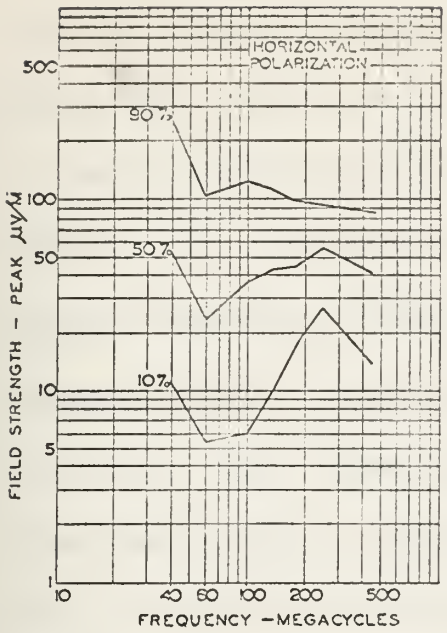


Fig. 2—Motorcar-ignition radiation, horizontal polarization. Peak field strength versus frequency for a 10-kilocycle band. 90, 50, and 10 per cent of all cars and trucks produce less than the field strength indicated by the curves. Receiving antenna 35 feet high and 100 feet from road.

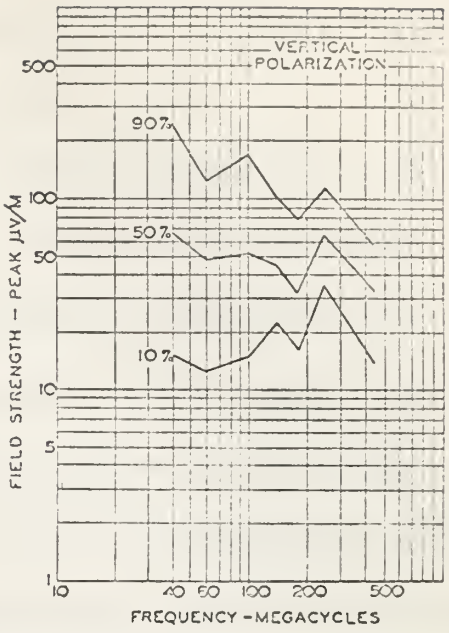


Fig. 3—Motorcar-ignition radiation, vertical polarization. Peak field strength versus frequency for a 10-kilocycle band. 90, 50, and 10 per cent of all cars and trucks produce less than the field strength indicated by the curves. Receiving antenna 35 feet high and 100 feet from road.

"Ignition noise on the V.H.F. and U.H.F.," C. M. Dean, QST, Vol. 28, no. 1, January, 1944.

Summary: The problem of electrical disturbances in mobile reception is investigated. Some of the basic problems of radio interference are reviewed and the characteristics of ignition are presented.

Interference in the region about 100 mc is considered. Problems caused by ignition noise and methods of trying to reduce the interference are discussed. An ignition spark is described as containing two components contributing the two parts of the wave train. A drawing shows the first part of the wave train as resulting from the capacative component while the "tail" is caused by the inductive factor. It is the latter which causes the greatest portion of radio interference. Adverse

effects on ignition of the gas mixture, brought about by methods attempting to reduce the inductive portion are mentioned.

Impulse noises of the type generated by ignition systems are of a complex nature. The wave form consists of a fundamental and a large number of harmonics These harmonics decrease in amplitude with increasing frequency, presenting a proportionately smaller energy factor to the receiver. Thus, if the fundamental of the impulse is a low frequency of the order of 100 kc, the harmonics at 100 mc will be quite weak. However, the receiver has a definite pass band and this results in the reception of all harmonics falling within the pass band. Since this band is small in comparison to the over-all span of the harmonic spectrum, the amplitudes of harmonics accepted are essentially equal. Furthermore, because of their in-phase relationship, their amplitudes add up arithmetically at the initiation and conclusion of the impulse. This results in a receiver input peak voltage proportional to the number of harmonics accepted by the pass band.

Shielding of the secondary of the ignition circuit causes reflections resulting in high-frequency modulation envelopes on the fundamental discharge wave. These complex circuit behaviors can give rise to very high voltage peaks along the lines. The various materials used for covering the high tension leads may introduce additional propagation effects. This introduces a "time-constant" effect which acts to build up enormous power peaks at resonant maxima in the line of slower "time-constant". Complex high-frequency envelopes of this type have been known to

develop voltage peaks of over 100,000 volts in a resonant line. Other variables in causing complex frequency spectra might be uneven gap spacing on the rotor and discontinuities in the system.

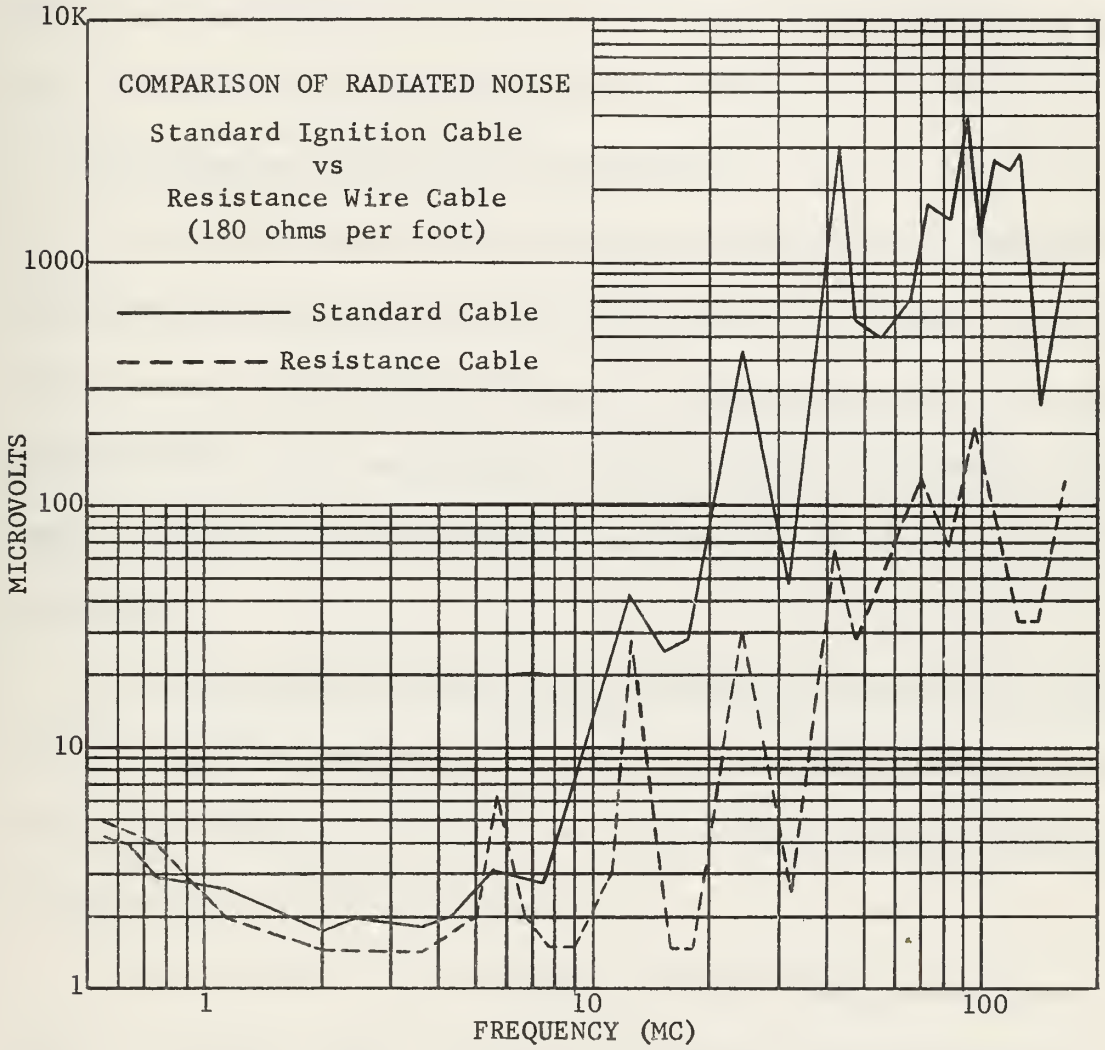
"Radio noise in aircraft engines," A. E. Teachman, Aeronautical Engineering Review, vol. 4, no. 8, August, 1945.

Summary: The results of extensive work during the war to reduce the radio noise problem on aircraft are discussed. One of the most important problems was ignition noise. Tests were run on aircraft engines with magneto ignition systems from about 1 mc to about 150 mc which was the limit of available measuring equipment at that time. All tests were made with radio noise meters installed in the aircraft with their antennas projecting through the top of the fuselage. The noise meters used were the RCA Model 312-C and Measurements Corp. Model 58. Engine speed was maintained constant at 1500 rpm.

The graph shown below gives the results of one of the tests comparing resistive cable with regular cable from about 1 mc to 150 mc. The crossover that takes place at the lower frequencies went unnoticed at the time data was taken but was attributed to having been caused by a transmitter, the strength of which varied during the interval of the test. In the range between 10 and 150 mc, the resistive cables give an average reduction in interference of 24 db.

The conclusions reached were that the principal radiated noise lies above 10 mc and that no resonant conditions are in evidence below 13 mc.

Less improvement is realized with resistor spark plugs than with distributed resistance wire and it may be surmised that the primary effect of resistor plugs in the reduction of radio interference is due to the fact that they limit the initial peak surge of current with corresponding reduction of the "shock wave" intensity.



"Radiation from car ignition systems," B. G. Pressey and G. E. Ashwell, Wireless Engineer, vol. 26, no. 304, January, 1949.

Summary: Measurements were made in the 40-650 mc band. The measuring equipment was a National Physical Laboratory Pulse Field Strength

Measuring Set which consisted of a tuned half-wave dipole, a wide band (2.5 mc) receiver in which are incorporated calibrated attenuators and a cathode-ray tube indicator unit. The cars used were 1940 models of the Vauxhall with various types of leads and suppression devices. Measurements were made at a distance of 30 feet from the center of the bonnet of the car on the same side as the ignition system. Aerial heights of 10 feet and 6 feet were used. Engine speed was 1500 rpm.

The following conclusions were reached:

1. The general level of the interference field shows no falling off with increase of frequency even at 650 mc but on the contrary, has a tendency to rise. The maximum variation from the general level is 9 db. The measurements on the basic system (one spark plug) showed that this interference spectrum is not substantially modified by the presence of the engine and body.

2 At a distance of 30 feet from the engine of the car and at a height of 6 to 10 feet from the ground the effective peak field strength as measured on a wide-band receiver is of the order of 10 uv/m for both horizontally and vertically polarized components.

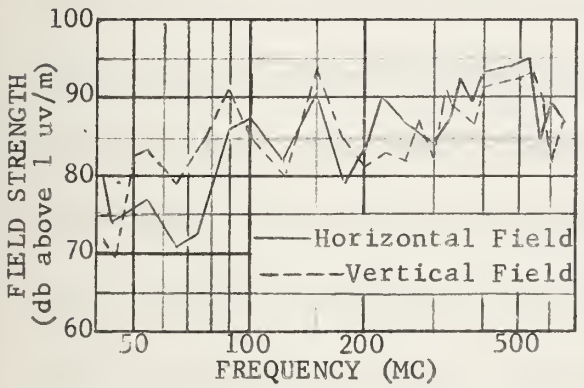
3. The variation in the amplitude of the individual pulses from the cars was normally about 10 db but the variation in the amplitude of those from the single plug basic system was only 3 db

4. The average suppression ratio obtained with block resistors of about 20,000 ohms and with resistive leads of about 5,000 ohms on the cars is of the order of 20 db in both cases. There are considerable

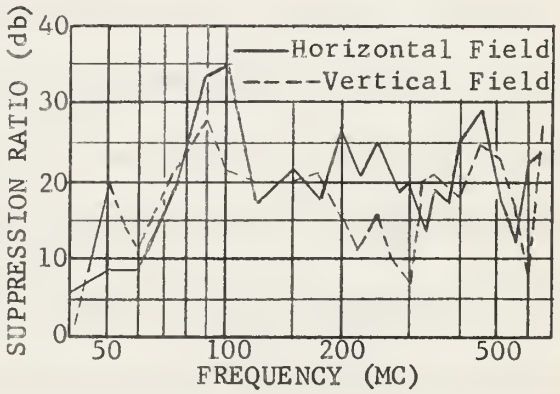
variations of the ratio with frequency giving values as high as 35 db and as low as 4 db. Also there was some indication of resonant effects in the system at certain frequencies.

5. The basic system showed that it was possible to have a negative suppression ratio of as much as 10 db.

6. The examination of the train of secondary pulses, which are associated with each nominal spark, has emphasized their importance under conditions of severe interference, but has shown that suppressors are more effective in the reduction of these trains than in the reduction of the primary pulse.



Field-strength of radiation from 6-cylinder cars at a distance of 30 feet.



Suppression ratio given by resistive leads on 6-cylinder car.

Estimating the peak amplitude of the pulses was very difficult and varied over the firing range by as much as 10 db. A change on frequency of a few megacycles was often sufficient to completely change the relative amplitudes of consecutive peaks. The values recorded were the maxima of the regularly occurring peaks which were observed, those peaks which occurred less than twice a second being ignored

"Car-ignition interference," W. Nethercot, Wireless Engineer, vol. 26, no. 311, August, 1949.

Summary: Nethercot disagrees with Eaglesfield's theory for explaining the frequency spectrum of ignition interference. The theory states that the spectrum is continuous and without gap, and that the radiated field is an impulse, short compared with the period of the carrier frequency up to frequencies of hundreds of megacycles (14). Nethercot uses a basic ignition circuit to give an expression for the current in the leads. The circuit consists of a transmission line terminated by a capacitor at one end and a gap at the other, with the engine block as an "earth plane". When the plug gap breaks down, current flows into it from the charged cable setting up traveling waves which are continually reflected at each end of the line. The energy stored in the capacitances and the high tension cables, all of which are charged to the breakdown voltage of the plug gap, is rapidly dissipated giving rise to the so-called capacitance component of the ignition spark. A succession of such discharges may occur before the final inductive or flame discharge occurs.

For a single line system considered by Nethercot, using 5 kv breakdown voltage, the current at the first maximum is 75 amperes. The current consists of a series of abrupt steps but the envelope is oscillatory with a frequency of approximately 30 mc. The effect of shortening the high tension cable is to reduce the time interval between the steps, increase the peak value of the current and increase the oscillation frequency of the envelope. The radiation from a current of this form is complex.

The radiation will have a continuous spectrum although its intensity will not be independent of the frequency (as in Eaglesfield's theory). Peaks should occur at the envelope frequency, which has been calculated to be in the region of 30-50 mc, and also at the frequency corresponding to the time interval between successive steps in the current wave. This was calculated to be about 300 mc.

This theory neglects the effect of the distributor gap which also sets up traveling waves in the leads. These produce different frequencies and thus would complicate the frequency spectrum. Nethercot did not consider other factors which would affect the radiation such as various lengths of the leads in an actual system, screening of the body of the car, and effects of the initial breakdown which are of very rapid duration.

"Car ignition radiation," C. C. Eaglesfield, Wireless Engineer, vol. 28, no. 328, January, 1951

Summary: This paper extends the theory given in his previous article (Wireless Engineer, vol. 23, October 1946). Previous theory postulated that the radiation from an unsuppressed ignition system is impulsive and that the effect on a receiver is independent of the frequency to which the receiver is tuned. This paper extends the theory to cover resonances and the addition of suppressing resistors. The previous paper derived an equation for expressing the equivalent peak field as

$$\frac{u}{4\pi cR} \cdot \frac{AEB}{L} \text{ volts/meter}$$

u - $4\pi \times 10^{-7}$ henry/meter

c - 3×10^{8} meter/sec

B - Receiver bandwidth in cps

R - Distance in meters

E - Sparking voltage in volts

L - Inductance of loop in henrys

A - Area of loop in square meters

This equation took account of only the inductance in the system as causing the field. Eaglesfield develops new equations which take into account the impedances of the system other than the inductances, and the effect of the addition of resistors on the radiation. Using approximations for values of resistance at frequencies other than d-c, for values of inductance and capacitance of the system, sparking voltages and area of the loop, fields were calculated which were compared with values measured by Pressey and Ashwell. Satisfactory agreement was obtained for the approximations made and for the frequency band covered.

The following conclusions were made:

1. The radiated field is still shown to be impulsive and affects all receivers in a way independent of their turned frequency. However, the impulsive field is amplitude modulated by the impedance of the ignition system at the receiver frequency.

2. In the unsuppressed case, the effect of resonances is apparently small in the band from 40 to 650 mc

3. Suppression by distributed resistance is much more satisfactory, since there will not likely be resonances within the band.

"Aircraft radio interference measurements", M. M. Newman, R. C. Schwantes, and J R. Stahmann, Transaction AIEE, vol. 71, pt 2, September, 1952.

Summary: Previous work on determining wave shapes and the statistical distribution of impulsive interference transients is reviewed. Waveforms were recorded of typical atmospheric interference, corona, and electric equipment transients such as motor brush interference. Techniques for measurement of transients and equipment to be used were discussed. The paper also shows how an oscillograph, capable of faithfully reproducing the interference pulses and their effects on receiving equipment, provides the basic information necessary for developing effective methods of interference reduction either at the source or by circuitry at the receiver.

"Measurement and suppression of VHF radio interference caused by motorcycles and motor cars," C. Egidi and E. Nano, IRE Transactions on Radio Frequency Interference, vol. RFI-3, no. 1, May, 1961.

Summary: The problem of ignition interference and its reduction has beem emphasized in Europe, due to the simultaneous growth in both the number of motor vehicles, and in the number of FM and TV receivers. The paper reports the results of a large number of interference measurements made on automobiles and motorcycles. The data include the effects of various suppression schemes. As a result of these measurements, and taking into account existing European standards, a draft of an international standard was prepared for submittal to CISPR (International Special

Committee on Radio Interference). (see Appendix B). This proposed standard covers methods of measurements and limits of interference. Three groups of measurements were carried out-- 1) a popular car under various conditions, 2) a group of high-priced Italian and foreign cars, and 3) small groups of Italian cars.

Measurement conditions were as follows:

Instrument	Stoddart NM-30A (URM-47)
Sites	Terrace atop a building (approx. 15 x 20 meters)
	Inside a large hall (94 x 112 meters, height 10 meters)
Frequencies	54, 110, 200, and 400 megacycles
Polarization	Horizontal and Vertical
Antenna height above ground	2 meters, 3 meters
Position of car	Fixed, with front facing dipole
Engine speed	Approximately 3000 rpm
Horizontal separation of center of engine and dipole	10 meters.

It was observed that measured values did not, to a significant extent, depend on the engine speed, provided it was sufficiently above idling speed With reference to the ignition coil, the "reinforced type" used in high-speed cars gave significantly higher interference levels The shielding effect of the hood was also checked; at 400 mc, it reduced interference 18.6 db. Various suppression methods were tried and the use of cables with distributed resistance and normal plugs appears the best practical solution.

The popular cars tested still exhibited a high interference level after suppression. A study is being made of the ignition sparks.

Examples of interference produced by a car without suppression, and with two different means of suppression are shown below.

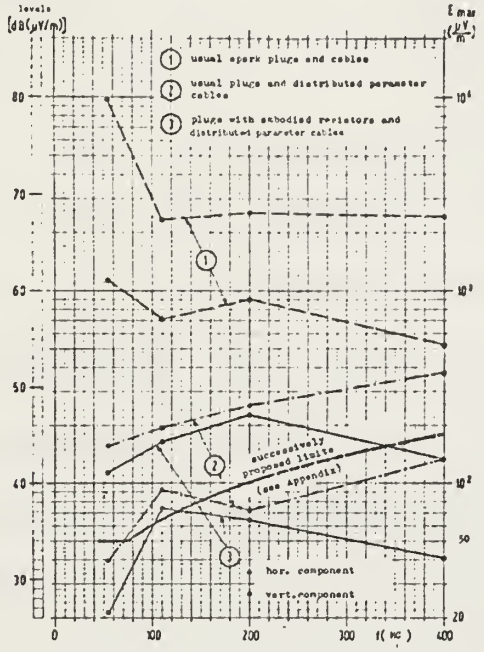


Fig. 7—Example of interference produced by a car without suppression and with two different means of suppression incorporated.

5 Interference Measurements on a 1962 Chevrolet.

In order to determine the frequency range and magnitude of the ignition noise radiated by a common modern car, measurements were made of the fields produced by a 1962 Chevrolet with a V-8 engine. The ignition schematic is shown on the following page in Fig. 1 and Fig. 2 is a photograph showing the placement of ignition components in the car.

Measurements were made at the Naval Air Intercept Training Facility site near Point Pinos at Pacific Grove, California. The site was chosen because of the low ambient noise level in the area as well as the availability of power to operate the equipment. Figs. 3 and 4 are photographs taken at the site indicating the relative positioning of the car under test, the antenna positions and the station of the operator and the receiving equipment making the measurements.

The car was positioned parallel to and approximately 58 feet from a 25 feet high wall of reinforced concrete (one wall of a building). The car was parked on a rough macadam parking lot surface which extended to the wall on the one side and about 60 feet to the front and to the rear of the car. The parking lot extended about 5 feet on the other side of the car bordering on an area of ice plant. This ice plant area was 90 feet wide with an eight feet high chain link fence at the far boundary.

For this test, the engine was run at 1500 rpm and readings were made of the fields detected at each of two locations. Two antenna tripods were positioned in front of the car on the line of its center. The first was arranged so the antenna center was 3 feet forward of the engine and 52 inches

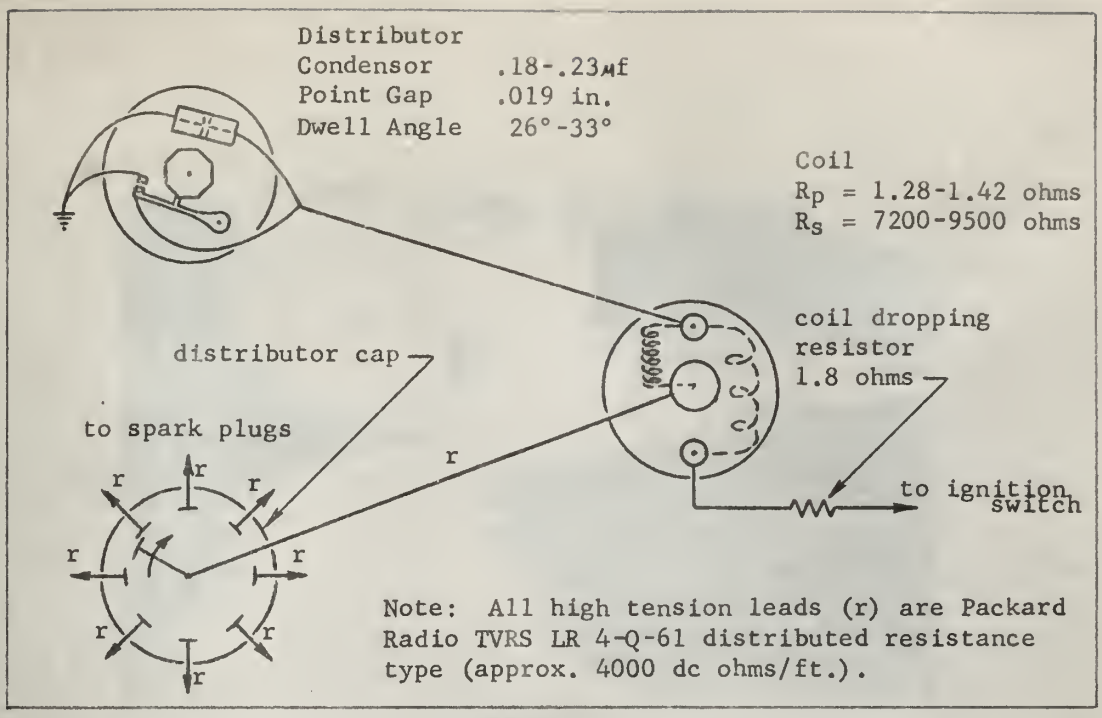

Distributor
Condensor .18-.23μf
Point Gap .019 in.
Dwell Angle 26°-33°
Coil
R_p = 1.28-1.42 ohms
R_s = 7200-9500 ohms
coil dropping resistor 1.8 ohms
distributor cap
to spark plugs
r
to ignition switch
Note: All high tension leads (r) are Packard Radio TVRS LR 4-Q-61 distributed resistance type (approx. 4000 dc ohms/ft.).

FIGURE 1

Ignition Schematic
1962 Chevrolet V-8

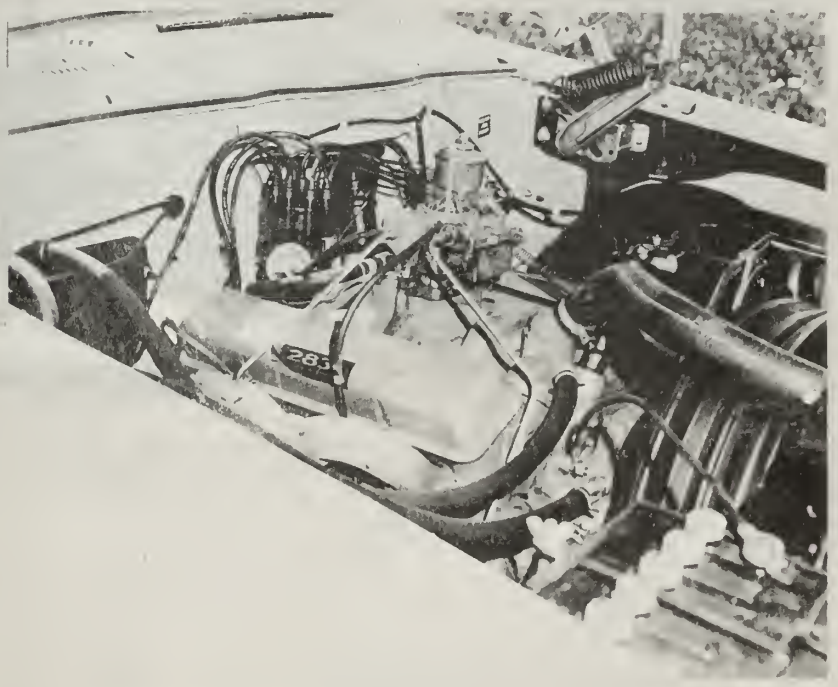


FIGURE 2

Under-hood view -- 1962 Chevrolet V-8. Carburetor air filter removed to show placement of distributor, coil and high tension leads.

FIGURE 3

View of test site showing terrain features and relative positions of car, antennas and measuring equipment.

FIGURE 4

View of test site from roof of building shown in figure 3. Spacing between antenna tripods is 30 feet.

from the ground. (Approximately 1 foot above the top of the radiator--the position specified by MIL-I-16910A). At lower frequencies measured with the dipole antenna, the 3 feet distance resulted in measurements being made in the near field. Results so obtained are not absolute indication of true field intensities since the antenna factor used was a far field parameter. The second tripod was positioned to place the antenna center 33 feet (10 meters) forward of the front of the engine and 6 feet high. These distances were approximately those specified by the European standards. Although the horizontal distances were the same, these antenna heights were not used for measurements made with the AN/PRM-1 and its loop antenna, where the antenna height was about 4 feet at both locations.

The frequency spectrum examined was from 0.15 to 10,000 mc and about five points were read in each decade of the range The range was covered by the AN/PRM-1 using its loop antenna, the TS-587/U and URM-17 using their respective dipoles and the URM-42 using a discone antenna. The specifications for these equipments are listed in Appendix C.

Except for frequencies below 25 mc where a loop antenna was used, the horizontally polarized field was measured at all frequencies examined. The engine speed was normally 1500 rpm but was also varied between 1000 and 2000 rpm as a check at several frequencies and found to produce no significant variation in the reading obtained. At two frequencies, readings were also taken with the hood open and are plotted with the results from other measurements.

Because of the impulse nature of the radiated interference, the average

or field intensity circuits of the measuring equipment were not used. Measurements were made using the quasi-peak and peak reading functions of the equipment. The results are illustrated graphically in charts 1 through 4 showing the quasi-peak and peak field strength measured (in db above 1 uv/m) as a function of frequency. On each chart, some portions of the frequency spectrum are cross hatched to indicate the level of ambient noise (including receiver noise) obtained with the engine not running. These represent a range of frequencies where the operation of the engine made no appreciable change in the value observed with the engine not running. The abrupt changes of this ambient level shown on the charts are not so much the result of actual changes in ambient level but are primarily because of changes in antenna-to-detector gain of the equipment, especially when a change of band was made. For the spectrum above 25 mc where primary attention was devoted to horizontal polarization, the levels measured with the hood open and with the antenna vertical are also shown on the charts.

Several other factors affecting the shape of the graph can be attributed to differences in equipment. Since the interference was impulsive in nature, the bandwidth of the receiving equipment is directly related to the amount of frequency components of the impulse which are passed on to the detector; hence, wider bandwidth equipment indicates a higher level of interference for a given level of impulse noise. For the equipment used in this investigation, a graph of relative bandwidth (in db above 1 kc) vs frequency is included in Appendix C. The bandwidth is the effective im-

pulse bandwidth, chosen here as 1.06 times the 6 db bandwidth.

The TS-587/U, a class IV equipment, here used to make measurements in the 28--400 mc frequency range, has basic features not common to the other three equipments used. In adjusting the TS-587/U prior to making a measurement at each frequency, the receiver noise is eliminated at the output of the detector for the zero input condition by decreasing the sensitivity of the receiver. This is done by adjusting the detector bias until a zero output is obtained. Therefore, low level readings of interference are not detected with respect to the same reference as the other equipments used where receiver noise is not biased out.

The quasi-peak weighting circuit of the TS-587/U has a charge time constant of 2 milliseconds and a discharge time constant of 620 milliseconds, while the other equipments have charge-discharge time constants of 1 and 600 milliseconds respectively. Since the impulse type interference investigated had pulse peaks with widths a small fraction of a microsecond (much less than 2 msec), the effect of the longer time constant was to give the quasi-peak readings made with the TS-587/U a lower value than would be measured with the other equipment.

The other important factor affecting the spectrum shape was the use of the loop antenna with the AN/PRM-1 for measurements at frequencies from .15 to 18 mc. Since this loop was oriented to receive vertically polarized waves, all values at frequencies below 25 mc are indicative of the strength of the vertically polarized wave. Although mixed polarization introduces errors in the results from measurements using a loop antenna, most readings

were made at the lower frequencies where such errors would be reduced.

Meter readings observed with the AN/PRM-1 and the URM-42 were converted to equivalent peak and quasi-peak field strength using the factors included with the equipment. However, since the TS-587/U is a class IV equipment, its readings were first converted to equivalent microvolts at the antenna terminals by substitution, using a Hewlett-Packard Model 608C as the calibrating signal generator, and then converted to uv/m field strength using the appropriate dipole conversion factor. This calibrating procedure was also used for readings made with the URM-17, since the two equipments had an overlapping range near 400 mc, and readings of the two meters could be compared in this area to determine bandwidth effects and effects of the difference in quasi-peak circuits.

To facilitate this comparison and to resolve an apparent discontinuity of results obtained with the two equipments at 400 mc, a further more detailed survey was made of the spectrum from 386 to 406 mc with the two equipments taking readings in this overlapping frequency range. Each reading was calibrated at the site by substitution For the field measurements 3 feet forward of the engine, the URM-17 dipole position was within 1/2 inch of the position occupied by the TS-587/U dipole when using that instrument However, both dipoles were approximately 50 inches from the ground as opposed to the 52 inch height used in previous measurements.

For the measurement 10 meters forward of the engine, the height again was about 6 feet for both antennas. The results of this detailed survey near 400 mc are illustrated graphically in charts 5 and 6.

The results at the 3 feet distance (chart 5) show a rapid rise and fall of peak values over the range as well as a separation between the results of the two equipments that is not quite constant. The quasi-peak values at 3 feet do not vary as rapidly but exhibit a wider separation.

At the 10 meters distance (chart 6), the peak readings of the two equipments are fairly constant with frequency and are separated by a nearly constant 12 db; not coincidentally, this corresponds to the difference in bandwidth between the URM-17 and TS-587/U at 400 mc. The difference in quasi-peak results between the two equipments shows some variation with frequency and is about 19 db at 400 mc. Allotting 12 db of difference to bandwidth dissimilarities, approximately 6 db separation can be attributed to quasi-peak circuit differences, while detector bias for receiver noise may account for some portion of the difference.

The retaking of readings in the neighborhood of 400 mc also provided a demonstration of the superiority of the 10 meter distance for making measurements. Although the readings near 400 mc were taken about a week after the readings over the entire spectrum of investigation had been made, the points at 400 mc at the 10 meter distance reproduced very closely and were noted to be moderately independent of the exact distance from engine to antenna. A change in distance of one foot produced no significant difference in the readings obtained. However, at the 3 feet distance, the position of the antenna center appeared to be critical, with a small change of position (1 to 2 inches) producing a noticeable change in results. For example, a change of height from 52 inches to 50 inches produced a change

in results of from 2 to 9 db. The reproducibility of results at this short distance appears to be difficult, and a comparison of readings made of radiation from vehicles with different body contours would have little meaning.

An examination of the spectrum of ignition interference obtained (charts 1-4) in light of the foregoing discussion, should be viewed as three spectral bands because of differences in polarization and equipment characteristics: .15 to 25 mc as a measure of vertical polarization; 25 to 400 mc, the horizontally polarized field measured by the TS-587/U; and the region 400 to 10,000 mc indicating the horizontal field measured by the similar instruments URM-17 and URM-42.

Charts 7 through 10 compensate for indicated level differences caused by bandwidth dissimilarities between equipments and bandwidth variation with frequency by presenting interference level--in db above 1 uv/m/kc--as a function of frequency. These charts are obtained from charts 1 - 4 by using the bandwidth characteristics of the equipment included in Appendix C. The presentation on a per kilocycle basis allows a more realistic evaluation of the effect of the ignition interference on a susceptible receiver of known bandwidth.

The following conclusions can be drawn from the results of this investigation;

1. The radiated spectrum of ignition interference from a typical modern car is extremely wide extending into the microwave region. The spectrum exhibits very prominent maxima at certain frequencies (in this

case, the 400 to 1000 mc region) and the peak value may vary quite rapidly and through an extremely wide range over the spectrum.

2. At distances of 10 meters or more, the radiated ignition interference drops to a low level at frequencies below 25 mc. With the low gain antenna (loop) used in this experiment, the ignition interference was below the receiver noise.

3. The 10 meters distance is superior to the 3 feet distance to insure reproducibility of results and to minimize the effect of the automobile body as a parasite of the receiving antenna.

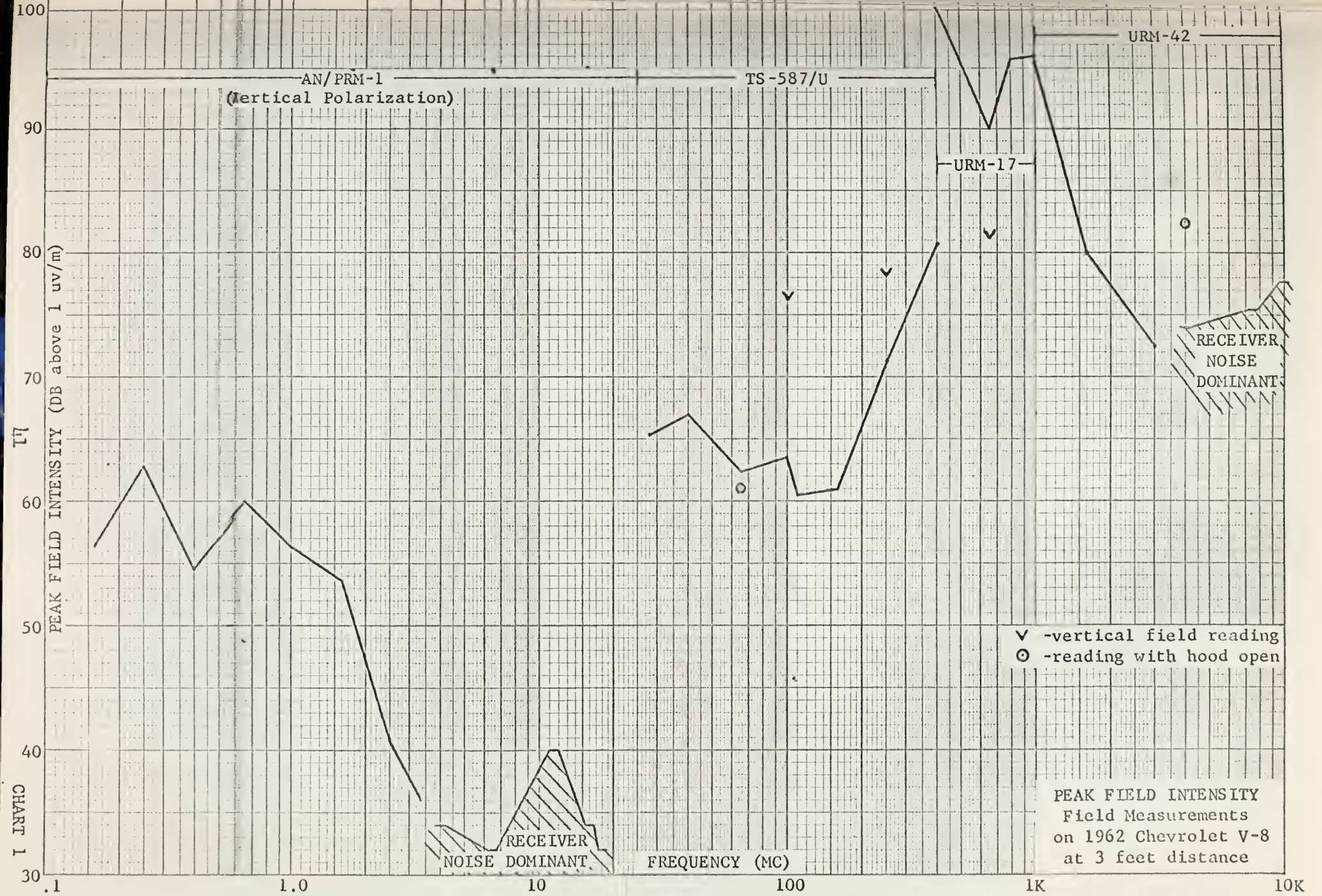
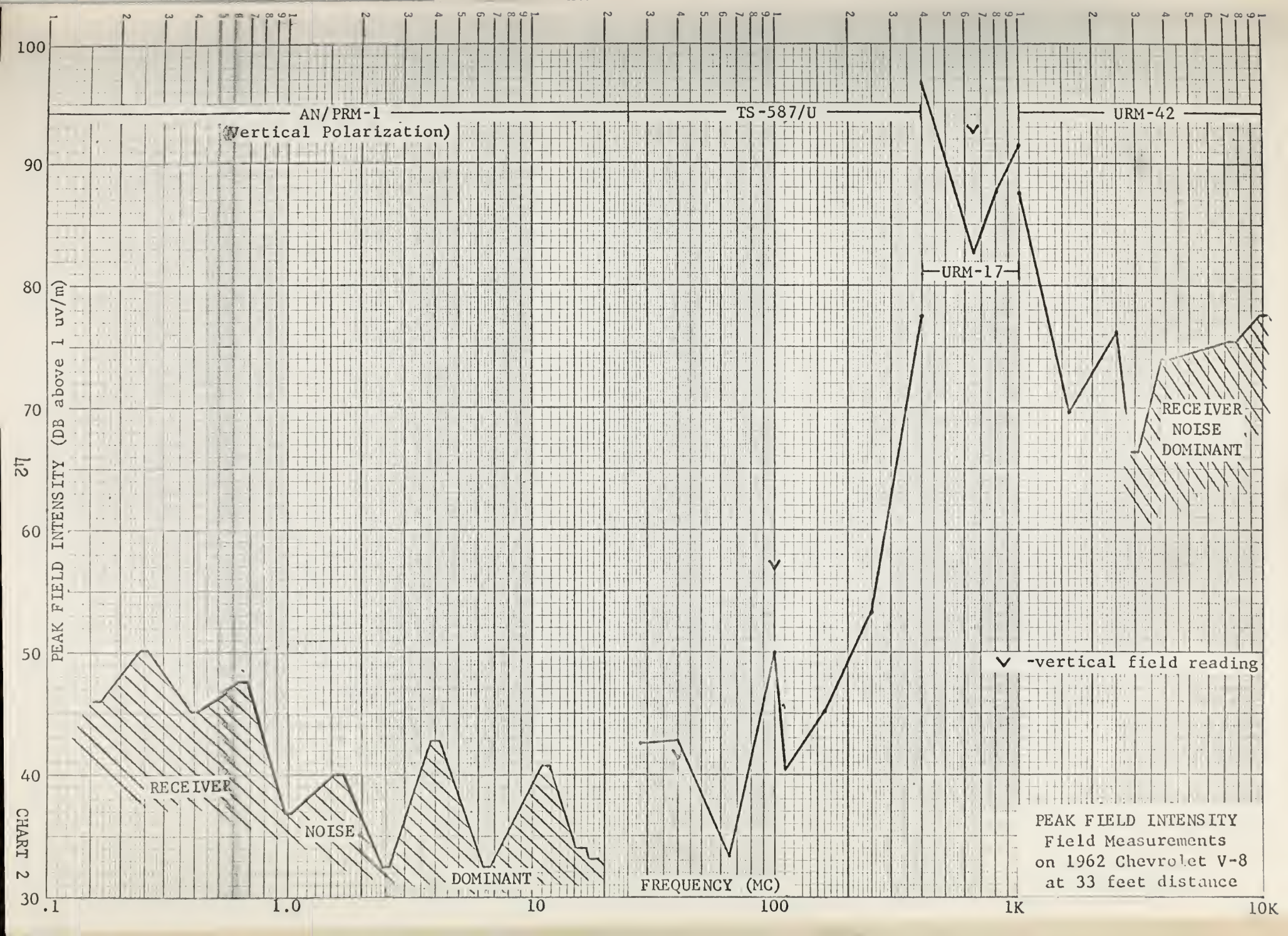
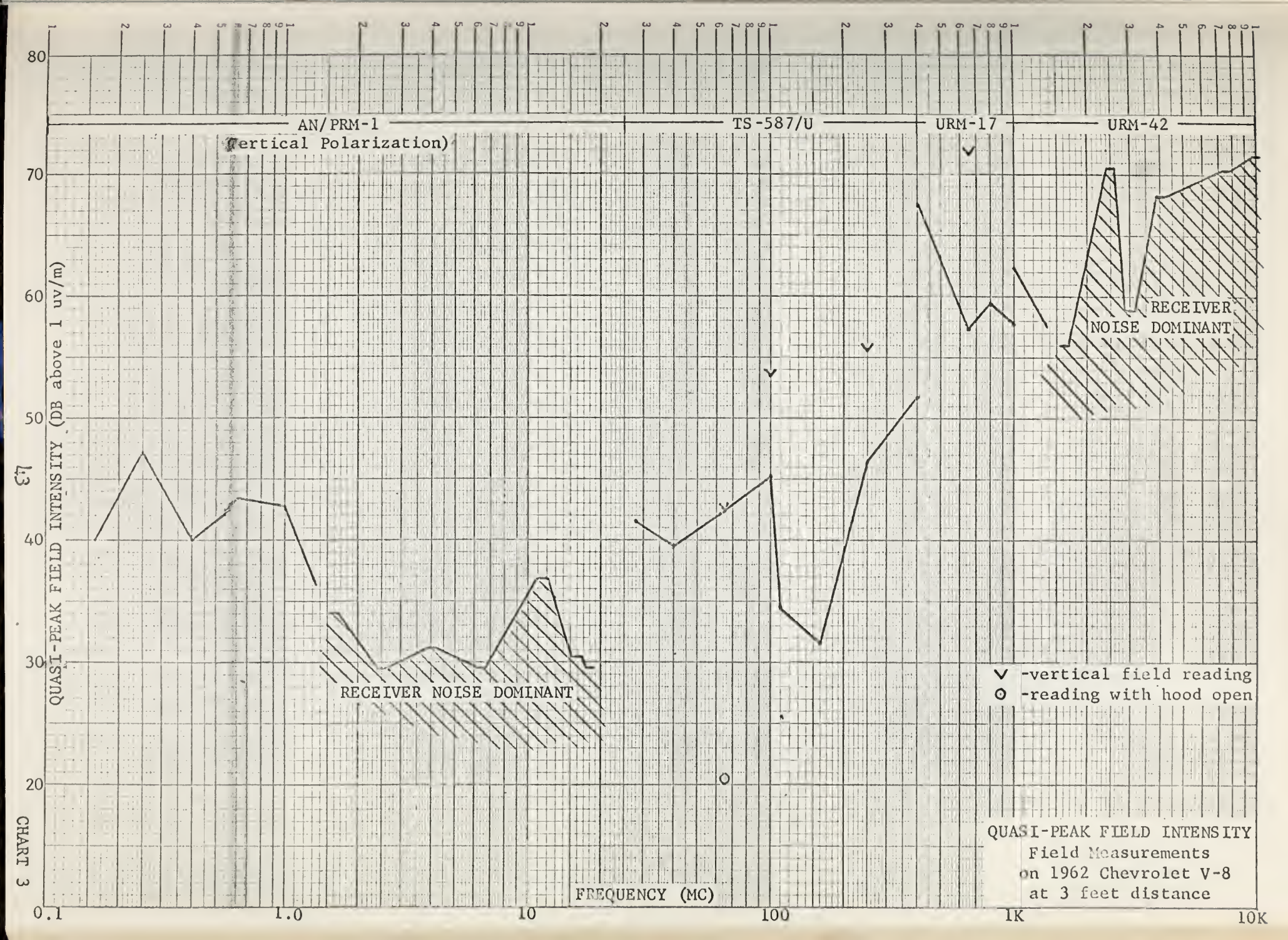
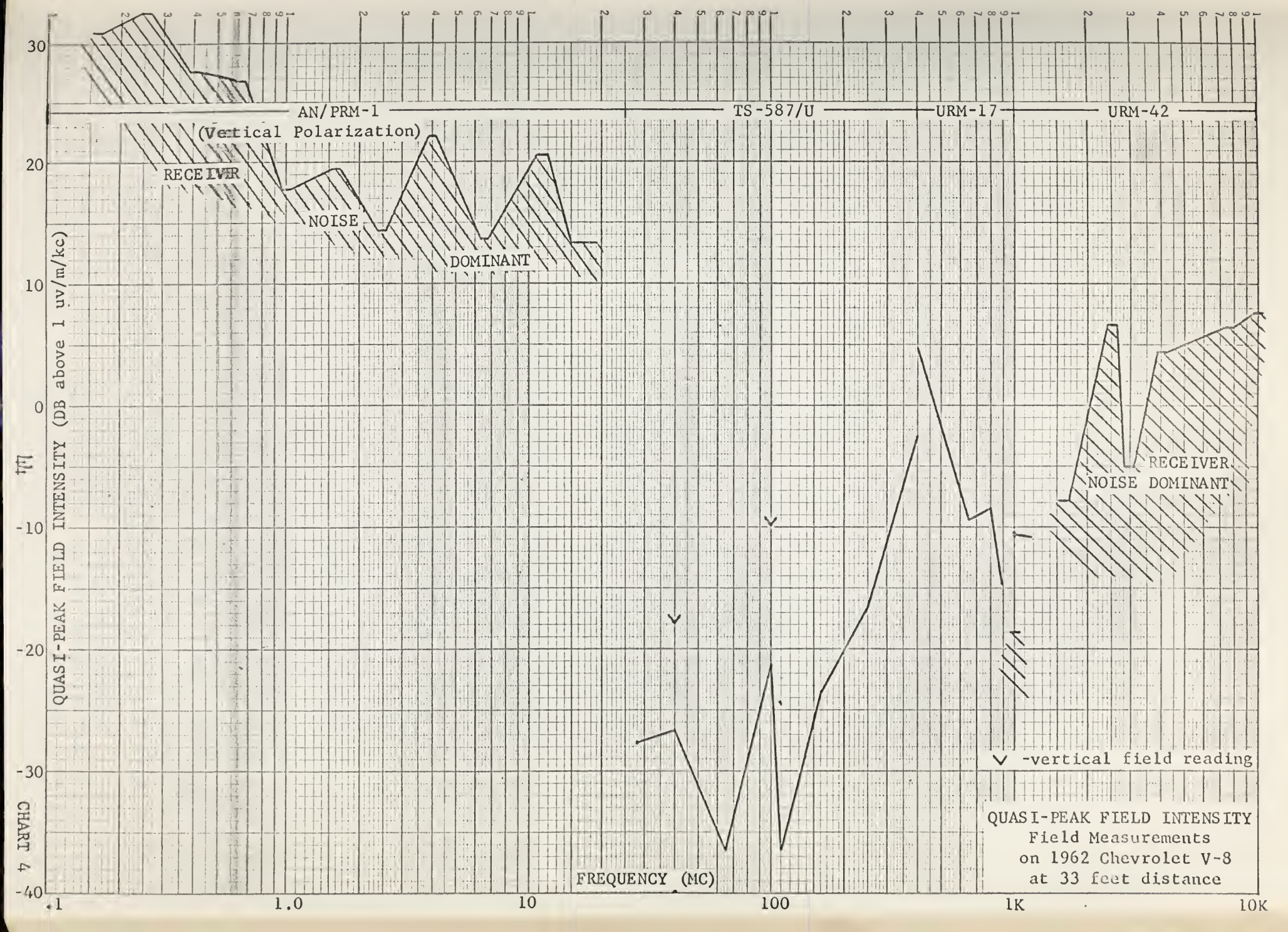
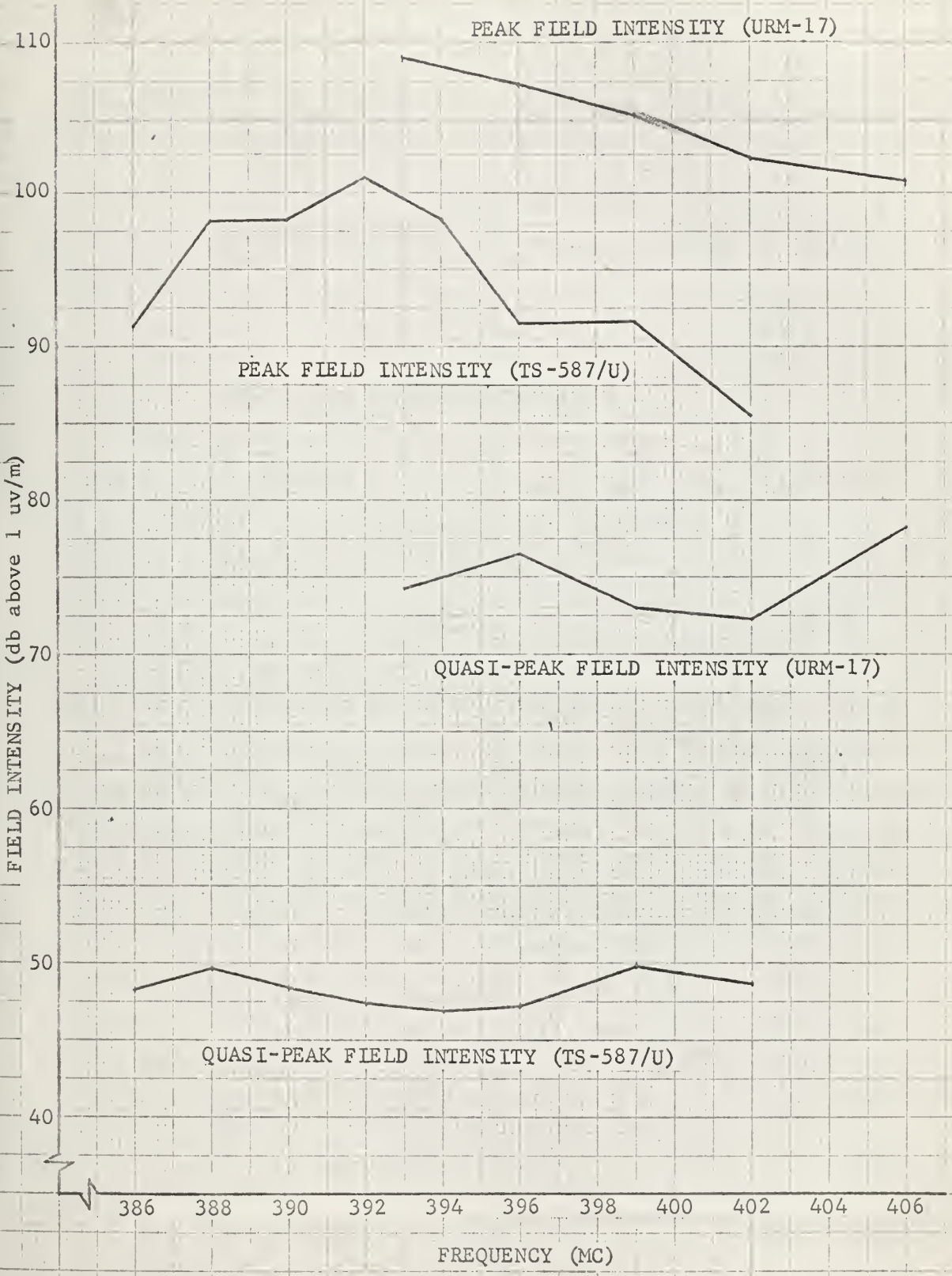

AN/PRM-1
(Vertical Polarization)
TS-587/U
URM-17
URM-42
PEAK FIELD INTENSITY (DB above 1 uv/m)
FREQUENCY (MC)
RECEIVER NOISE DOMINANT
RECEIVER NOISE DOMINANT
100
90
80
70
60
50
40
30
.1
1.0
10
100
1K
10K
-vertical field reading
-reading with hood open
PEAK FIELD INTENSITY
Field Measurements
on 1962 Chevrolet V-8
at 3 feet distance

CHART 1


AN/PRM-1
(Vertical Polarization)
TS-587/U
URM-42
URM-17
PEAK FIELD INTENSITY (DB above 1 uv/m)
100
90
80
70
60
50
40
30
RECEIVER
NOISE
DOMINANT
RECEIVER
NOISE
DOMINANT
-vertical field reading
PEAK FIELD INTENSITY
Field Measurements
on 1962 Chevrolet V-8
at 33 feet distance
FREQUENCY (MC)
.1
1.0
10
100
1K
10K
CHART 2

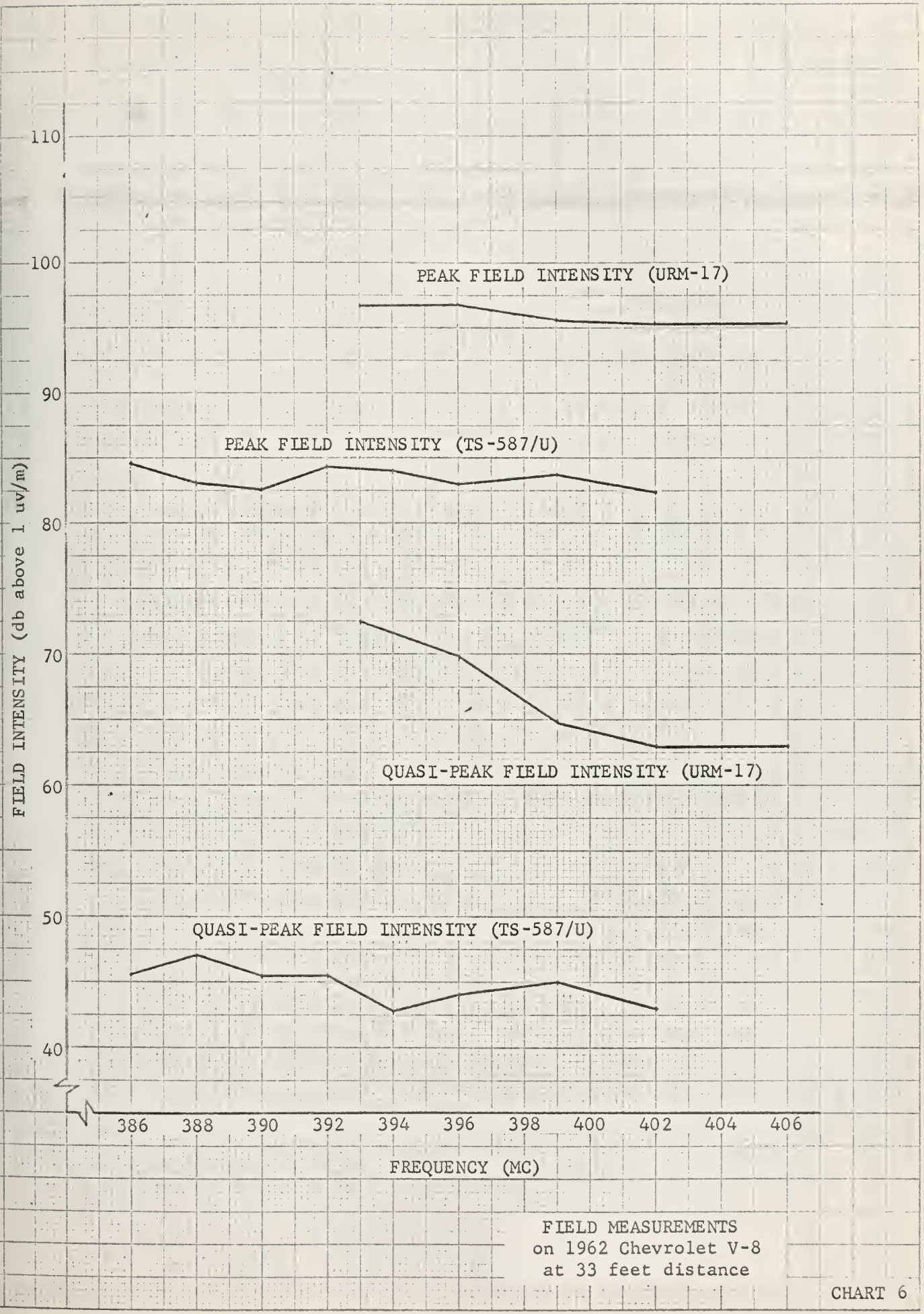

AN/PRM-1
(Vertical Polarization)
TS-587/U
URM-17
URM-42
RECEIVER NOISE DOMINANT
RECEIVER NOISE DOMINANT
QUASI-PEAK FIELD INTENSITY (DB above 1 uv/m)
80
70
60
50
40
30
20
FREQUENCY (MC)
0.1
1.0
10
100
1K
10K
V -vertical field reading
O -reading with hood open
QUASI-PEAK FIELD INTENSITY
Field Measurements
on 1962 Chevrolet V-8
at 3 feet distance
CHART 3


AN/PRM-1
TS-587/U
URM-17
URM-42
(Vertical Polarization)
RECEIVER
NOISE
DOMINANT
RECEIVER
NOISE DOMINANT
QUASI-PEAK FIELD INTENSITY (DB above 1 uv/m/kc)
FREQUENCY (MC)
30
20
10
0
-10
-20
-30
-40
.1
1.0
10
100
1K
10K
V -vertical field reading
QUASI-PEAK FIELD INTENSITY
Field Measurements
on 1962 Chevrolet V-8
at 33 feet distance
CHART 4



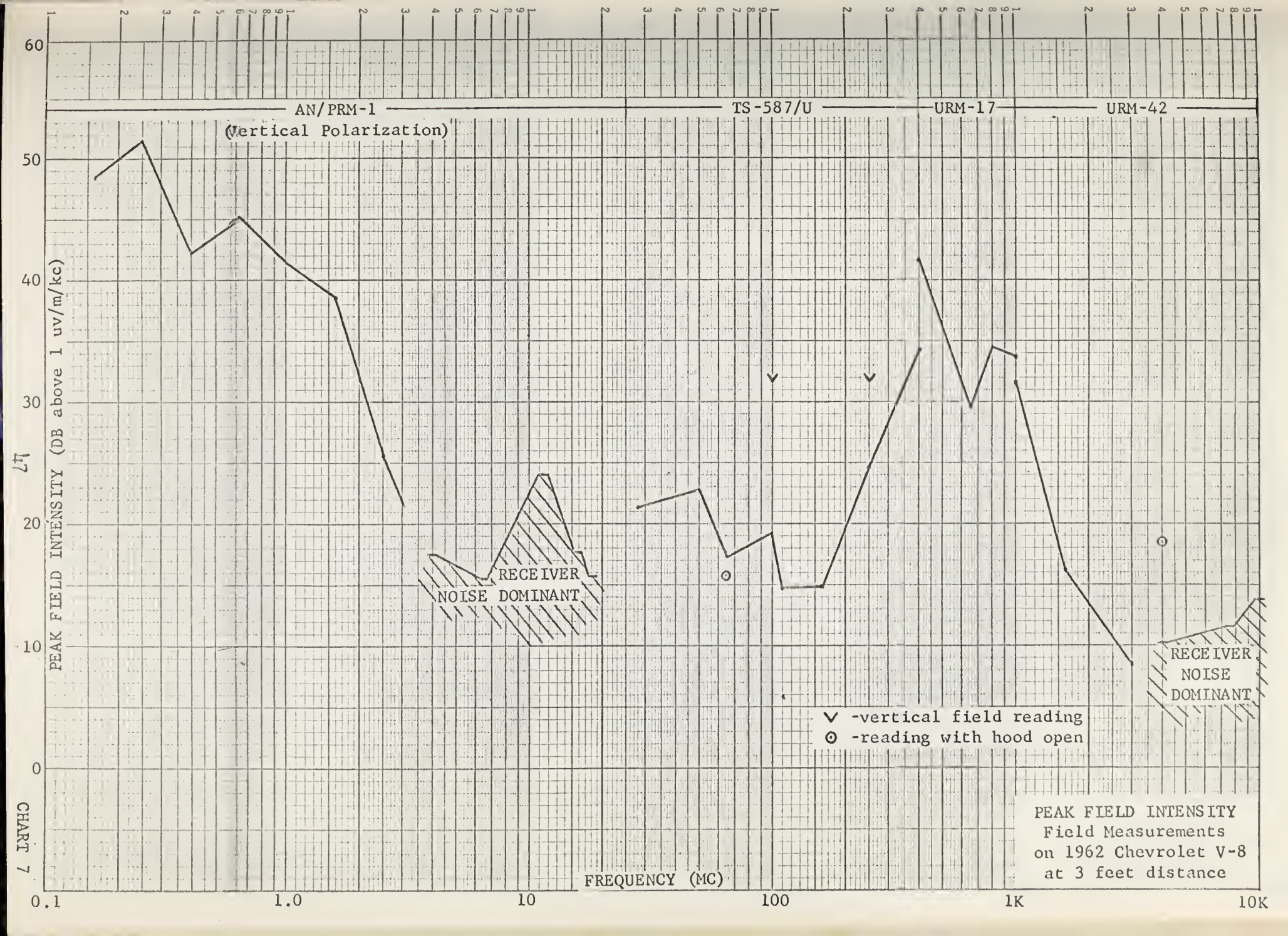
FIELD MEASUREMENTS
on 1962 Chevrolet V-8
at 3 feet distance

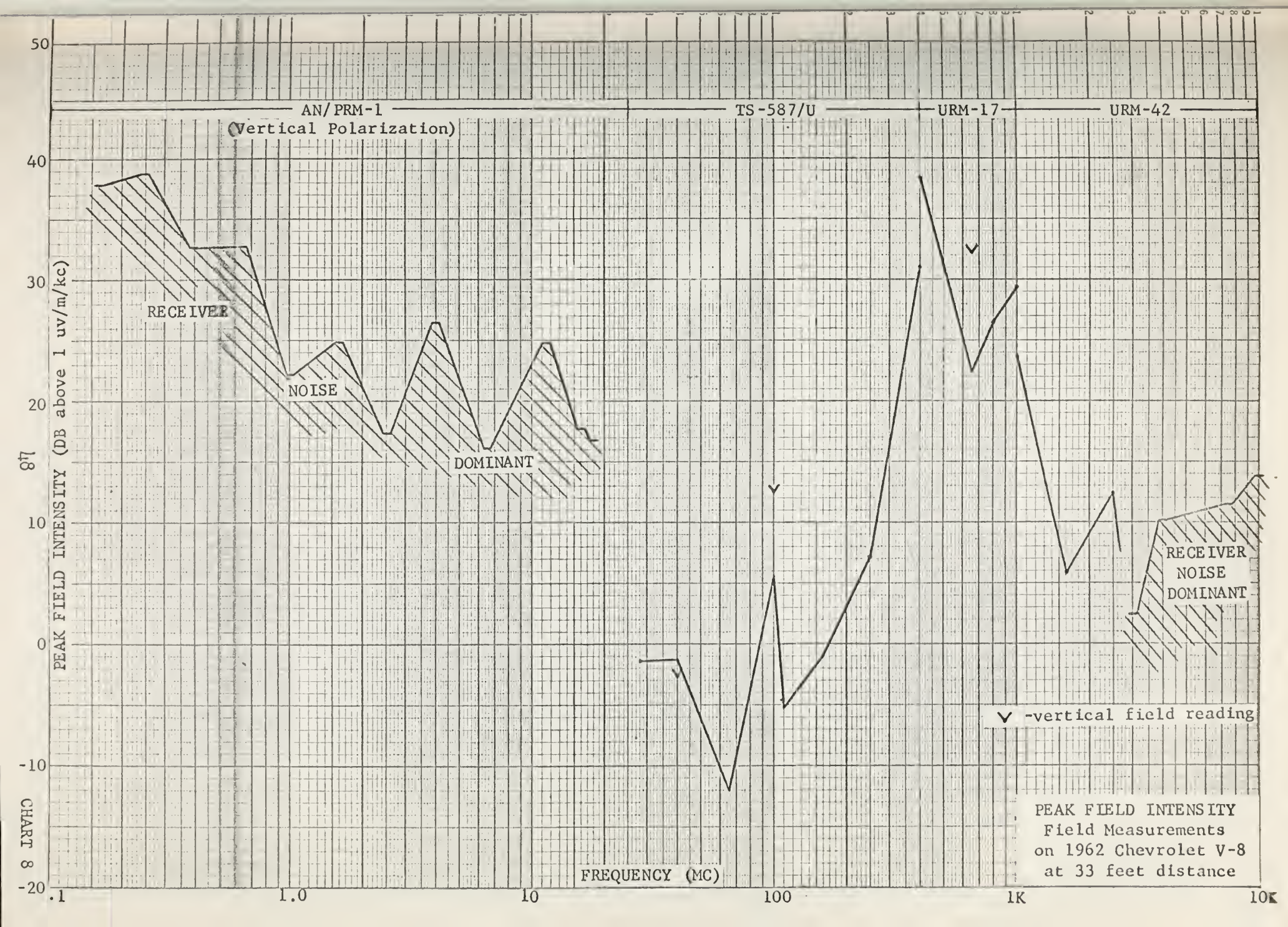
CHART 5

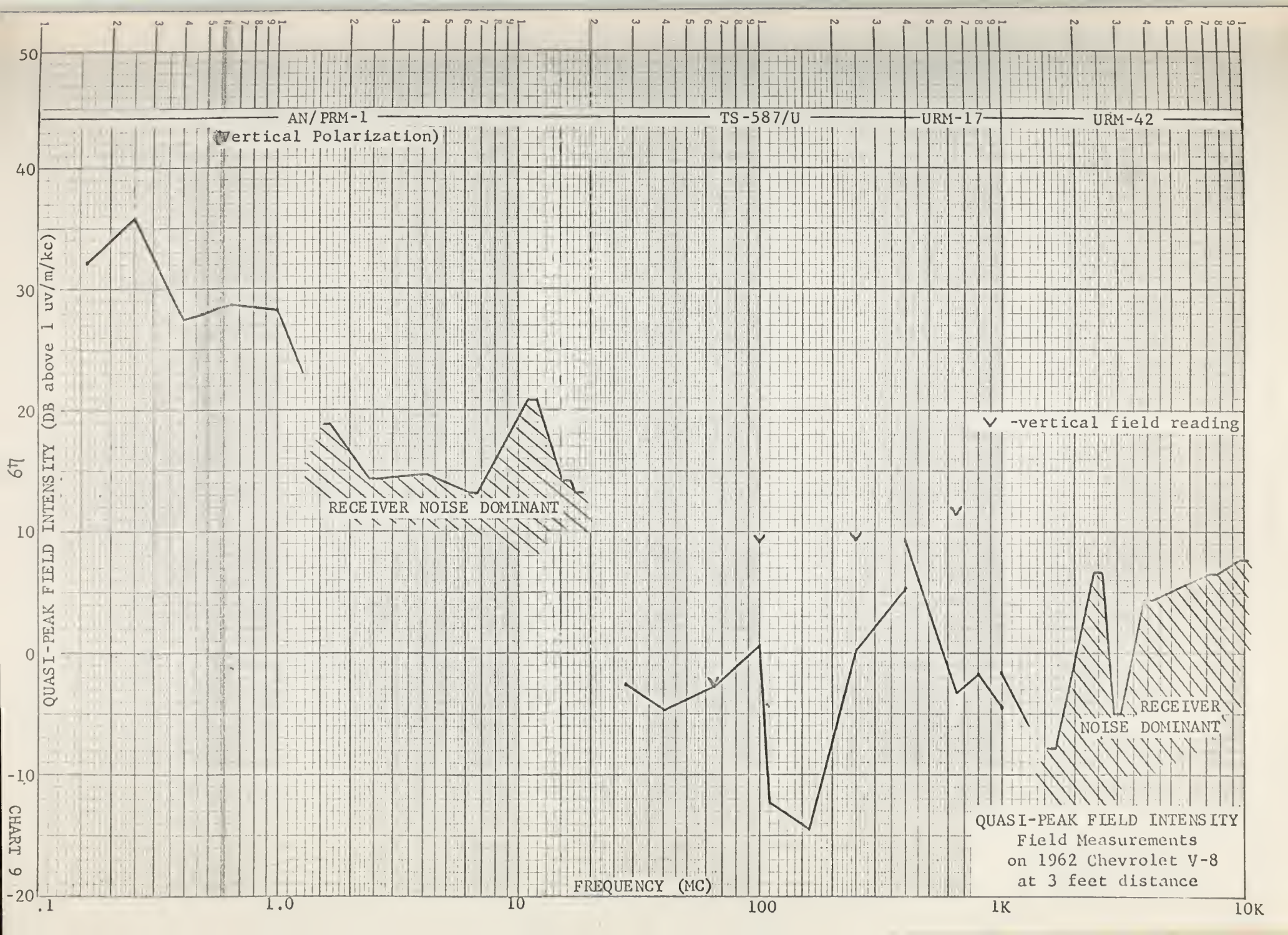


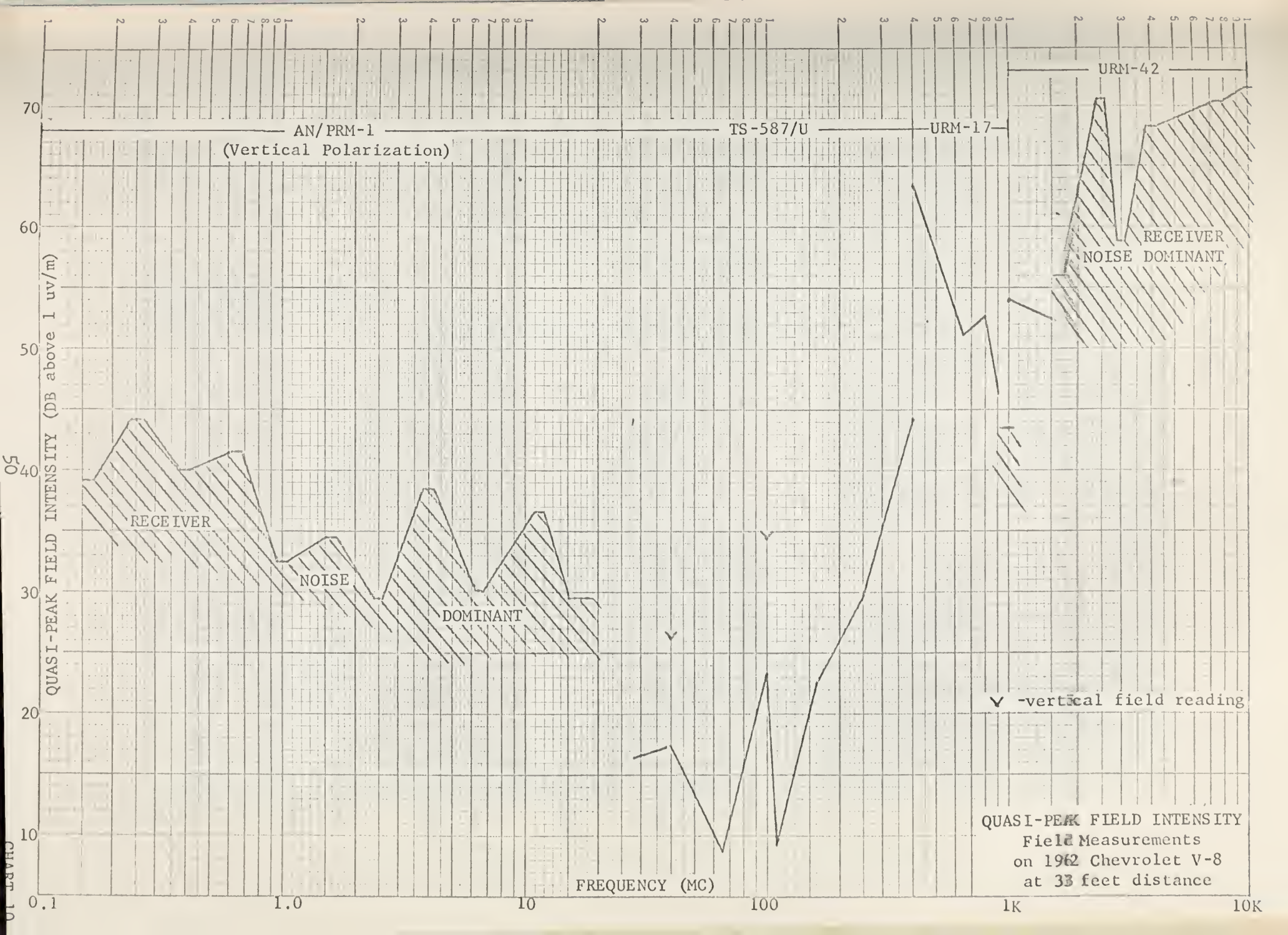
FIELD MEASUREMENTS
on 1962 Chevrolet V-8
at 33 feet distance

CHART 6


AN/PRM-1
TS-587/U
URM-17
URM-42
(Vertical Polarization)
PEAK FIELD INTENSITY (DB above 1 uv/m/kc)
RECEIVER NOISE DOMINANT
RECEIVER NOISE DOMINANT
-vertical field reading
-reading with hood open
FREQUENCY (MC)
0.1
1.0
10
100
1K
10K
60
50
40
30
20
10
0
47
CHART 7
PEAK FIELD INTENSITY
Field Measurements
on 1962 Chevrolet V-8
at 3 feet distance


AN/PRM-1
(Vertical Polarization)
TS-587/U
URM-17
URM-42
RECEIVER
NOISE
DOMINANT
RECEIVER
NOISE
DOMINANT
PEAK FIELD INTENSITY (DB above 1 uv/m/kc)
db
FREQUENCY (MC)
50
40
30
20
10
0
-10
-20
.1
1.0
10
100
1K
10K
V -vertical field reading
PEAK FIELD INTENSITY
Field Measurements
on 1962 Chevrolet V-8
at 33 feet distance
CHART 8


AN/PRM-1
(Vertical Polarization)
TS-587/U
URM-17
URM-42
QUASI-PEAK FIELD INTENSITY (DB above 1 uv/m/kc)
50
40
30
20
10
0
-10
-20
RECEIVER NOISE DOMINANT
V -vertical field reading
RECEIVER NOISE DOMINANT
FREQUENCY (MC)
.1
1.0
10
100
1K
10K
QUASI-PEAK FIELD INTENSITY
Field Measurements
on 1962 Chevrolet V-8
at 3 feet distance
CHART 6


AN/PRM-1
(Vertical Polarization)
TS-587/U
URM-17
URM-42
RECEIVER
NOISE
DOMINANT
RECEIVER
NOISE DOMINANT
QUASI-PEAK FIELD INTENSITY (DB above 1 uv/m)
FREQUENCY (MC)
70
60
50
40
30
20
10
0
0.1
1.0
10
100
1K
10K
V -vertical field reading
QUASI-PEAK FIELD INTENSITY
Field Measurements
on 1962 Chevrolet V-8
at 33 feet distance
CHART 10

6. Screen Room Measurements

The purpose of the screen room measurements was for preliminary experimentation and investigation of a typical ignition system. These tests would give some indication of the limits of radiated frequency spectrum without the influences of the car body. Also permit comparison of various types and lengths of ignition leads on interference levels, waveform analysis and measurements on the frequency spectrum analyzer.

These various measurements were taken in a laboratory screen room as shown in Figs. 1 and 2, except for the spectrum analyzer measurements and peak values for regular leads with the TS-587. These were taken with the spectrum analyzer and RI-FI set in an adjacent screen room to prevent direct coupling of radiation into the I.F. section of the equipment. Previous measurements made with one spark plug as a radiation source in the screen room had given values of standing wave ratio of 16.9 db for quasi-peak readings. While for peak readings there was little indication of any standing wave effects. This is because of the random nature of the maximum value of radiated interference. Location of the antenna and radiation source were located at several places in the screen room to determine whether variations in readings were obtained. These tests verified the fact that for quasi-peak readings the antenna location would be somewhat critical and should be kept in the same location for comparative measurements between various types of leads.

Location of measuring antenna was as specified by MIL-I-16910A (SHIPS) except that the distance from antenna to the center of the coil was

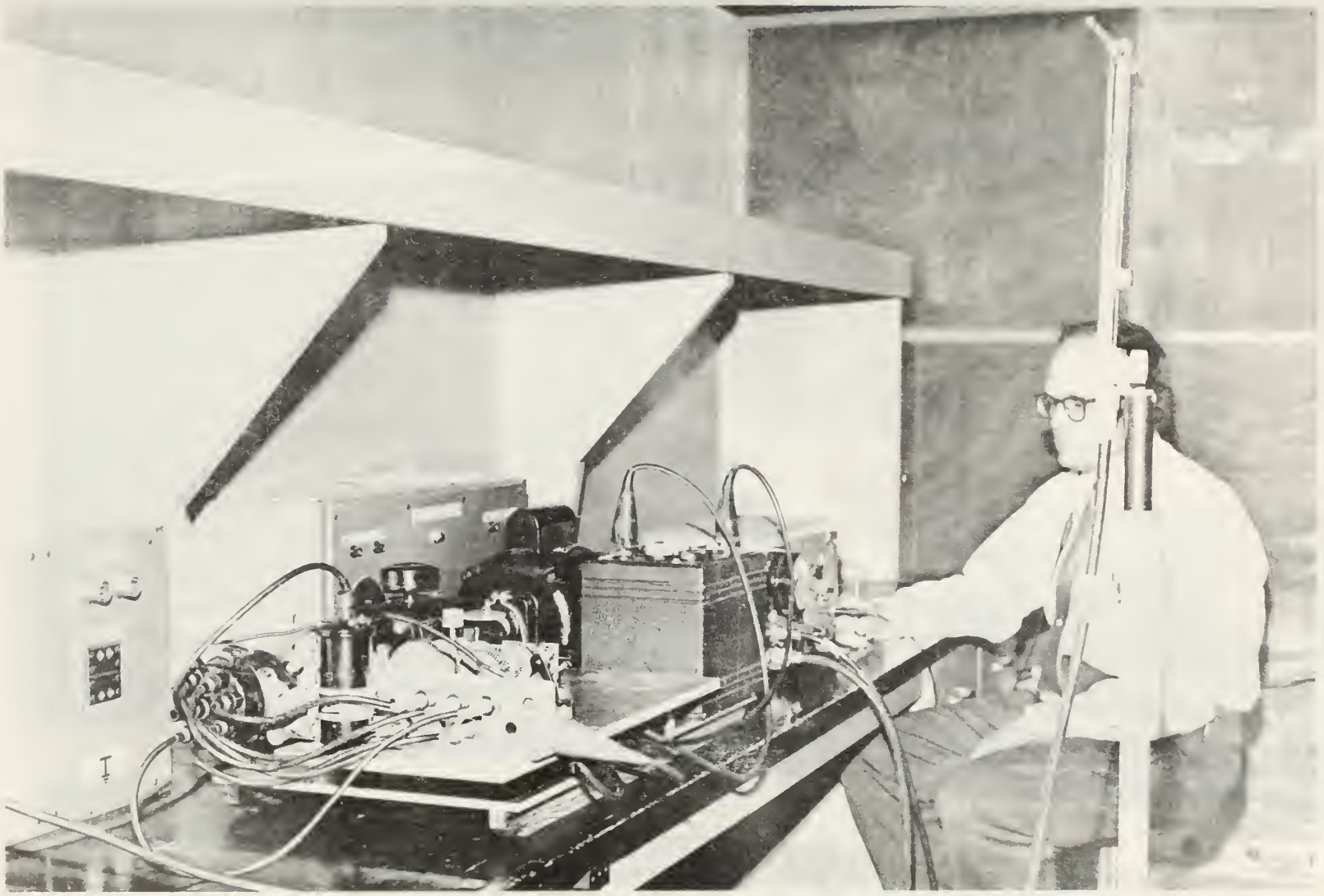


FIGURE 1. Arrangement of Equipment for Screen Room Measurements

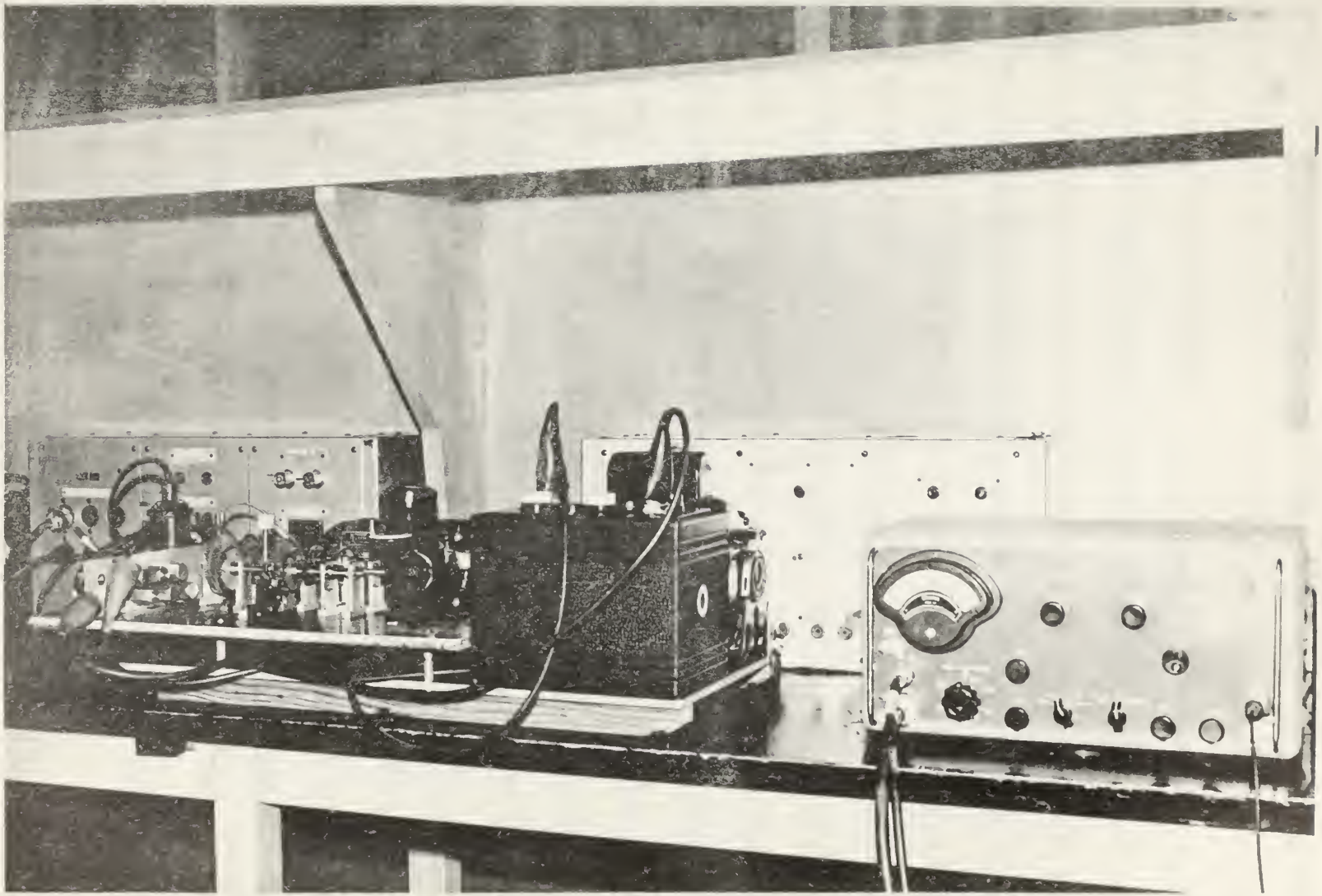


FIGURE 2. Arrangement of Equipment for Screen Room Measurements

three feet for all tests. Antennas were kept a minimum of 15 inches away from the side walls or ceiling at all times. This prevented any measurements at frequencies less than 40 mc with a resonant dipole. The loop antenna was used with the AN/PRM-1 for frequencies from 150 kc to 18 mc.

The ignition system used for the screen room measurements was an eight lobe distributor from a car several years old. The spark plugs were used, but the electrodes were cleaned and gap spacing was set at 0.032 inches. A six volt battery and coil were used with the distributor. The rotor of the distributor contained as an integral part an 8,000 ohm carbon resistor in series with the high tension circuit. The points and point condenser used were those that had been in the distributor for some time. The points were not noticeably pitted and looked representative of points that had been run a few thousand miles. The points were set to 0.015 inches maximum opening and gave a dwell time of approximately 60 per cent.

Only six plugs were used during the screen room test. The plugs were mounted through holes in a piece of sheet aluminum and held in place by brass cap nuts to prevent any radiation from the spark itself except through the ceramic insulation of the plug. The plugs were connected to the distributor through either the low resistance wire that had been originally used with the distributor (hereafter referred to as regular leads) or through leads made of distributed resistance wire (hereafter referred to as long leads or resistive leads).

The six plugs were connected to fire in sequence for six point openings followed by two point openings corresponding to the omitted plugs and

then another sequence of six firings.

The regular leads that were used were quite short, ranging in length from eight inches to 20 inches and had a DC resistance of 0.2 to 0.4 ohms. The long leads were all the same length, 24 inches, including the coil to distributor high voltage lead and were made of Packard Radio TVRS LR 4-Q-61 distributed resistance wire. These each had a DC resistance of approximately 9,000 ohms. These leads were purposely all made the same length to determine if any resonance effects could be related to lead length. In addition to these two sets of high voltage leads, a third set of short leads ranging in length from eight inches to 14 inches made of the same distributed resistance wire, was used at seven frequencies to determine the effects of changing lengths.

The test bench ignition system was driven by a four pole induction motor through a variable speed fluid coupling. For the data plotted on the charts the distributor was driven at a speed of 1,000 rpm $\pm$ two per cent corresponding to an engine speed of 2,000 rpm or a vehicle cruising speed of 30-40 mph.

Procedures for taking the various measurements were as follows:

1 Radio interference set tuned to each test frequency and calibrated if required for that set.

2. Antenna was tuned to the frequency under test and located as specified. In making the measurements, the ignition system was mounted in the longitudinal center of the screen room and the center of the receiving antenna was placed 36 inches from the coil such that it was at least 15 inches away

from the nearest wall or ceiling. For measurements below 25 mc, the AN/PRM-1 was used with the loop antenna. The loop was positioned one foot above the elevation of the ignition system and 36 inches from the coil. Measurements were made to only 18 mc since the RI-FI meter would not calibrate above that frequency From 40 to 1000 mc resonant dipoles were used with the equipment. From one kmc to 10 kmc using the URM-42, a discone antenna was used, spaced the same as the other antennas. Figs. 1 and 2 are photographs of the screen arrangement with the URM-17 and Appendix C is a tabulation of the specifications of the various equipments used in the measurements.

3. Ambient readings were taken with the ignition system being driven by the induction motor but without the battery connected to the coil.

4. Quasi-peak and peak reading were then taken for each test frequency with the system operating at normal conditions Readings were first taken with the long resistive leads and then with the regular leads.

a. One set of measurements were taken with the AN/PRM-1, TS-587/U, URM-17, and AN/URM-42 with the antenna parallel to the long dimension of the screen room. Antenna spacing was maintained for all test sets. The leads were interchanged to compare resistive leads versus regular leads. See charts 11 through 18.

b. Another set of measurements, shown on charts 22 and 23 were taken with the TS-587/U and URM-17. First with the antenna placed parallel to the short dimension of the screen room and then with the antenna parallel to the long dimension of the screen room. Again the ignition leads

were interchanged to give values for comparison of resistive leads versus regular leads.

c. At seven frequencies in the range 100 to 1000 mc additional measurements were taken with the short resistive leads. These measurements were for comparison with the other sets of leads to determine effects of lead length and impedance on the interference levels. See charts 19 and 20.

d. At several frequencies in the higher frequency range where it was feasible because of small antenna size, vertical polarization was measured to compare with horizontal polarization.

e. At four frequencies the speed was varied to determine if there was any change in interference levels. Increase of speed would increase the repetition rate of the impulses coming from the ignition system. However if the speed was above a certain minimum (approximately 600 rpm) there was no noticeable difference in the readings.

5. After quasi-peak and peak values were recorded at each frequency the antenna was disconnected from the RI-FI set and connected to a coaxial cable leading to the adjacent screen room for measurement and photographing on the spectrum analyzer. See Figs. 3 through 17. After recording the data from the spectrum analyzer a signal generator in the same screen room as the ignition system was connected to the coaxial line to calibrate the spectrum analyzer at the test frequency. This procedure was necessary to allow for cable loss between the screen rooms in determining the level of measured interference. At the higher frequencies the coaxial

cable loss was of such magnitude that it prevented calibration of the measurements with the signal generator.

6. After measurements were taken the various test sets were calibrated to give uv/m or uv/m/kc as follows:

a. AN/PRM-1 Radio Interference set - Meter readings were converted to actual uv/m and uv/m/kc by using the calibration charts with the equipment. The gain of the receiver was standardized at each test frequency by adjusting the calibration control to give the meter reading required by the calibration charts.

b. TS-587/U Noise meter set - Meter readings were converted to actual uv/m and uv/m/kc by using the method of calibration by substitution. Voltage from a signal generator required to duplicate the interference measurement was recorded and multiplied by the dipole factor to give uv/m. These readings were converted to uv/m/kc by using the effective bandwidth of the set at each frequency. Appendix C gives the effective bandwidth versus frequency.

c. AN/URM-17 Radio Interference set - Method of calibration was the same as for the TS-587/U. Effective bandwidths used are shown in Appendix C.

d. AN/URM-42 Radio Interference set - Meter readings were converted to uv/m and uv/m/kc by using the correction factors with the equipment. The gain of the receiver was standardized by using a noise generator (part of the URM-42) and setting the calibration control to reduce the audio output to zero. Effective bandwidths are shown in Appendix C.

With regular leads in the ignition system and using the TS-587/U as the interference measuring set for frequencies from 40 to 400 mc the intensity of the peaks was such that it caused direct coupling into the I.F. section. For these frequencies the TS-587/U was located in the adjacent screen room and the antenna coupled to the RI-FI set through the coaxial cable. This permitted measurements of the interference level and calibration was accomplished in the same manner as for the spectrum analyzer.

In analyzing the various charts of interference levels versus frequency with the several pieces of test equipment used it was necessary to correct for ambient noise and bandwidth differences. Bandwidths of the Radio Interference sets are shown in Appendix C. These were based on the 6 db bandwidths multiplied by 1.06 for correction of impulse noise (28). Magnitude of the output for impulse signals is a direct function of the bandwidth; as the bandwidth is increased the output increases. Therefore to correlate interference measurements between the measuring sets uv/m were converted to uv/m/kc

These corrections for ambient noise (where necessary) and bandwidth bring the amplitude versus frequency spectrum into close agreement considering the wide variations in amplitude resulting from resonant effects. Charts 11 and 15 show interference levels in uv/m before bandwidth corrections. Charts 12, 13, 16, and 17 give the results of conversion to standard interference units of uv/m/kc. Charts 14 and 18 give average values of interference levels versus freqency for quasi-peak and peak readings. These two charts also compare regular leads versus resistive leads and

give values for changes in interference levels per megacycle frequency change.

During the measurements the following observations were made:

1. Vertical polarization was approximately the same as horizontal polarization at the frequencies from 1000 mc to 10 kmc.

2. At 900 mc with the URM-17 the ignition lead from the coil to the distributor was interchanged. With regular leads on the ignition system changing the lead from the coil to distributor to a resistive lead reduced the peak reading by 7 db. However with resistive leads on the ignition system, changing the coil to distributor lead to a regular lead had little effect on the peak value.

3. With the AN/PRM-1 for frequencies below about 10 mc, with resistive leads, the quasi-peak readings were very erratic. This could indicate an amplitude modulated input resulting from modulation of the lower frequency components of the ignition radiation.

4. Wide variations in values measured were noted when the operator changed his position or items were moved in the screen room. Therefore it is necessary that the layout of the screen room be maintained and the operator assume the same position for each reading

Measurements taken with the spectrum analyzer are shown on chart 21. Peak readings were recorded by visual observation of the scope for a given time interval. A calibrating signal was then inserted at the antenna terminals to determine the magnitude of the peak value recorded This reading in microvolts (uv) was converted to uv/m by the appropriate dipole

factor. Comparing this chart with chart 11 for readings in uv/m from RI-FI sets shows approximately the same frequency spectrum form and the values compare closely to the quasi-peak values recorded on the Radio Interference sets Therefore this would indicate that the visual observations of peak values compare more favorably with quasi-peak values from the applicable detector weighting circuit. Reduction of interference levels by resistive leads from chart 21 indicate an approximate 11 db average difference. This compares with values of 12 to 30 db with an average of 20 db for differences between resistive and regular leads from chart 11.

Figs. 3 through 17 are photographs of the spectrum analyzer scope for various frequencies and types of leads. The frequency dispersion was 10 mc, the resolution bandwidth was 2 kc, and the sweep speed was 1 cps. A resonant dipole antenna was used for the frequencies 40 to 400 mc shown in Figs. 3 through 13 and for Figs. 14, 15, 16, and 17 the discone antenna was used. For the kilomegacycle region the spectrum analyzer did not have the separate input filters available to pass only those frequencies in the particular analyzer frequency band being used. Therefore as noted in the footnotes of Figs. 14 through 17 they include other frequencies which are not filtered out. However they verify the measurements made by the RI-FI sets in the kilomegacycle region and also give comparative values between regular and resistive leads.

The sweep speed was determined by several factors. A representation of the ignition pulse train is shown on page 68.

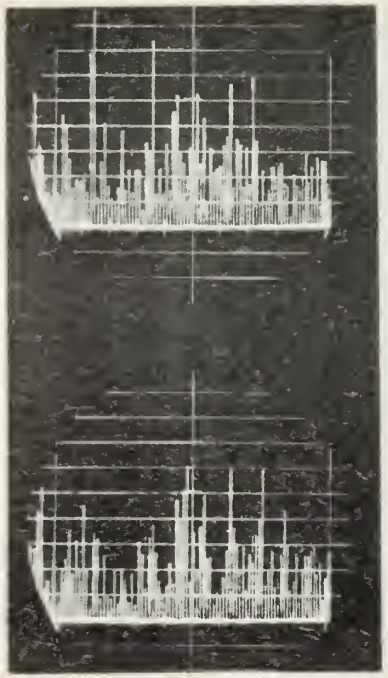


FIG. 3 . Center Freq. 40 Mc/s.[1] Top and bottom photos -- Regular leads with 4 db I.F. attenuation.

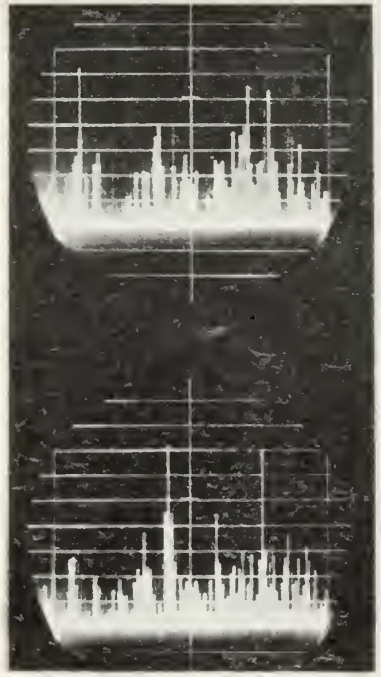


FIG. 4 . Center Freq. 60 Mc/s.[1] Top and bottom photos -- Regular leads with 10 db I.F. attenuation.

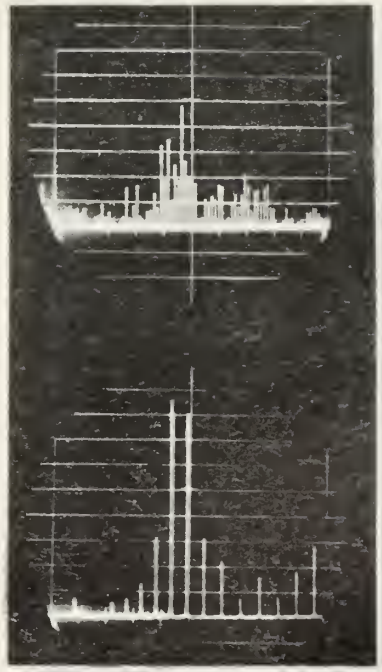


FIG. 5 . Center Freq. 60 Mc/s. Top photo -- Resistive leads with 0 db I.F. attenuation. Bottom photo -- One Mc/s markers.

SPECTRUM ANALYZER DISPLAYS

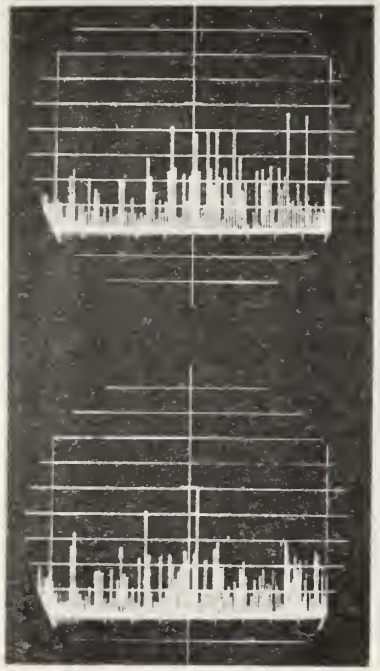


FIG. 6 . Center Freq. 100 Mc/s.[1] Top and bottom Photos -- Regular leads with 10 db I.F. attenuation.

FIG. 7 . Center Freq. 150 Mc/s.[1] Top and bottom photos -- Resistive leads with 0 db attenuation.

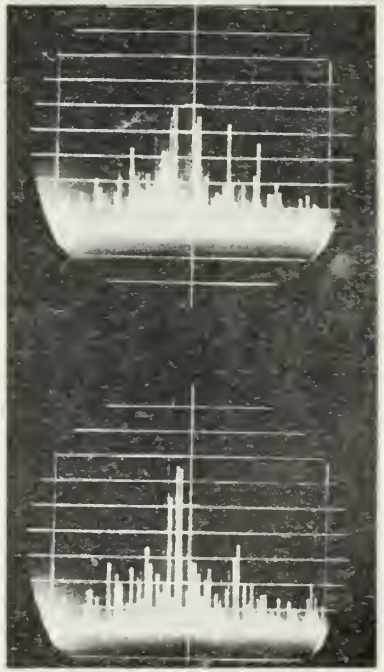


FIG. 8 . Center Freq. 200 Mc/s.[1] Top and bottom photos -- Regular leads with 8 db I.F. attenuation.

SPECTRUM ANALYZER DISPLAYS

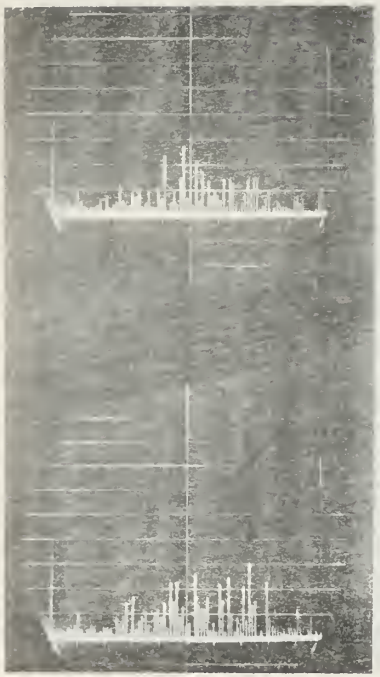


FIG. 9. Center Freq. 200 Mc/s.[1] Top and bottom photos -- Resistive leads with 0 db I.F. attenuation.

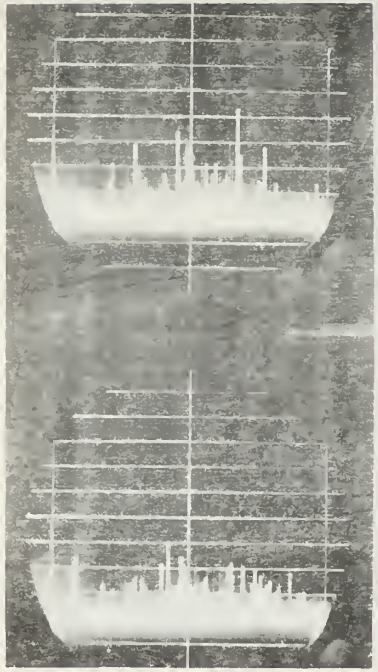


FIG. 10. Center Freq. 300 Mc/s.[1] Top and bottom photos -- Regular leads with 7 db I.F. attenuation.

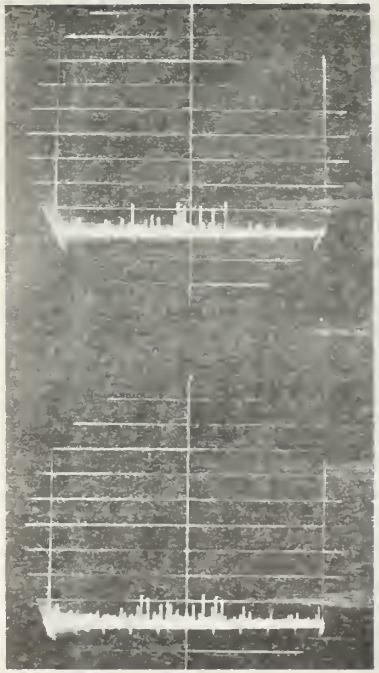


FIG. 11. Center Freq. 300 Mc/s.[1] Top and bottom photos -- Resistive leads with 0 db I.F. attenuation.

SPECTRUM ANALYZER DISPLAYS

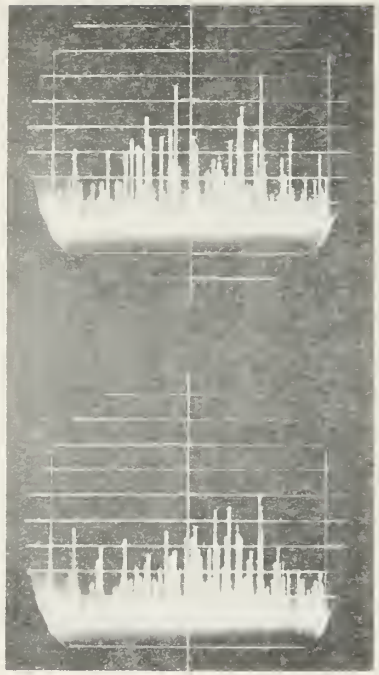


FIG. 12 . Center Freq. 400 Mc/s.[1] Top and bottom photos -- Regular leads with 4 db I.F. attenuation.

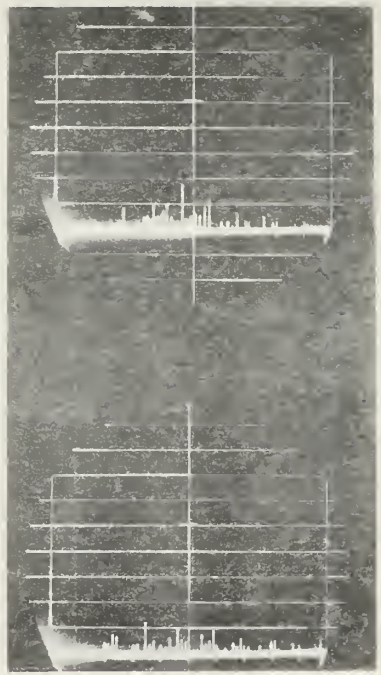


FIG. 13 . Center Freq. 400 Mc/s.[1] Top and bottom photos -- Resistive leads with 0 db I.F. attenuation.

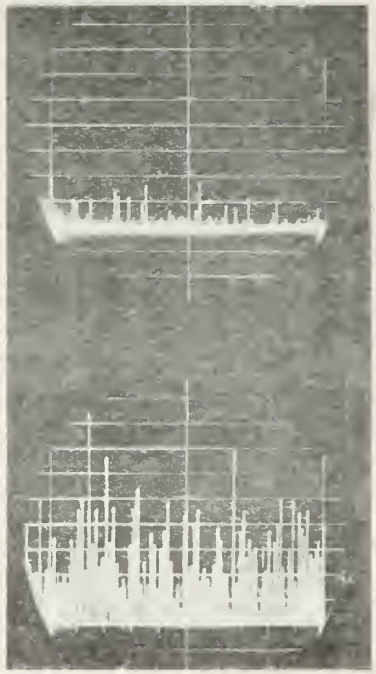


FIG. 14 . Center Freq. 2 KMc/s.[1,2] Top photo -- Resistive leads with 0 db I.F. attenuation. Bottom photo -- Regular leads with 3 db I.F. attenuation.

SPECTRUM ANALYZER DISPLAYS

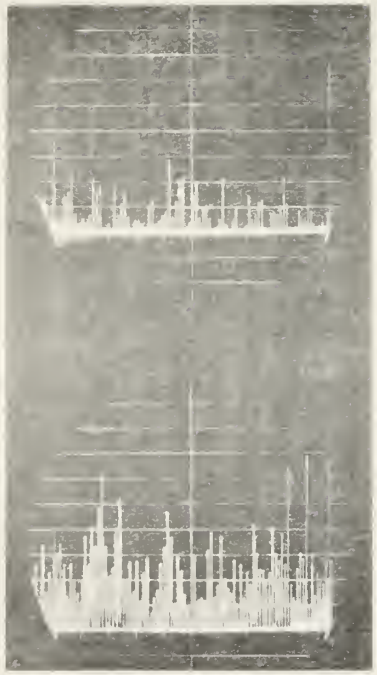


FIG. 15. Center Freq. 4 KMc/s.[1,3]
Top photo -- Resistive leads
with 0 db I.F. attenuation.
Bottom photo -- Regular leads
with 6 db I.F. attenuation.

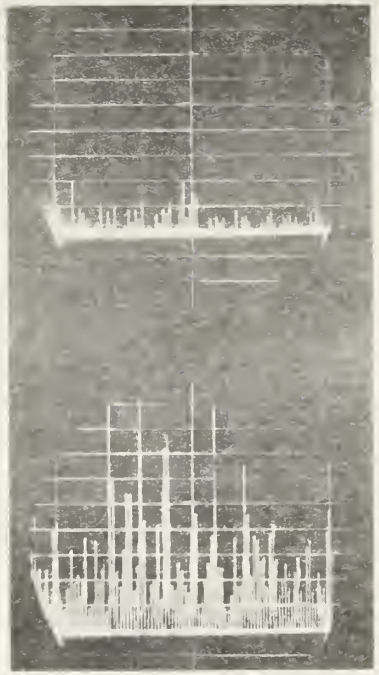


FIG. 16. Center Freq. 6 KMc/s.[1,4]
Top photo -- Resistive leads
with 0 db I.F. attenuation.
Bottom photo -- Regular leads
with 6 db I.F. attenuation.

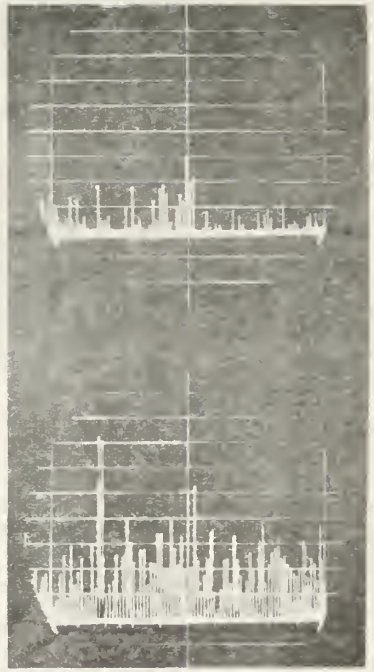


FIG. 17. Center Freq. 10 KMc/s.[1,5]
Top photo -- Resistive leads
with 0 db I.F. attenuation.
Bottom photo -- Regular leads
with 9 db I.F. attenuation.

SPECTRUM ANALYZER DISPLAYS

Note 1. All photographs were taken with the Spectrum Analyzer set as follows:

a. One second single sweep

b. Frequency dispersion - 10 mc.

c. Resolution bandwidth - 2 kc.

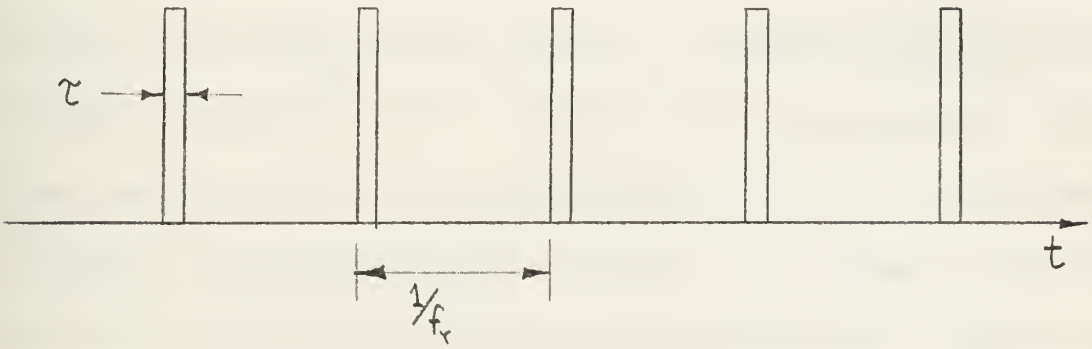
Note 2. Includes 4 15, 6.3, and 12 8 kmc frequency components.

Note 3. Includes 8 15, 12.3, and 1.9 kmc frequency components.

Note 4. Includes 2.95, 9.1, and 18.4 kmc frequency components

Note 5. Includes 3.23, and 6.6, and 20 2 kmc frequency components.

This figure considers only the initial breakdown current surge as a very narrow, large amplitude pulse and neglects the lower frequency oscillations which follow. A pulse width of 10^{-8} seconds is assumed and the pulse repetition frequency is 133 per second based on 1000 rpm and 8 sparks per revolution.



A signal composed of rectangular pulses of width at a pulse repetition frequency of f_r has a frequency spectrum:

$$e(t) = \tau f_r \sum_{n=-\infty}^{\infty} \frac{\sin(n\pi f_r \tau)}{n\pi f_r \tau} \cos 2\pi(f_c + nf_r)t$$

where for ignition pulses $f_c = 0$ (carrier frequency). This gives a characteristic $\frac{\sin x}{x}$ frequency distribution where the minima of the spectrum envelope occurs at frequencies $1/\tau$, $2/\tau$, ... away from f_c (or zero in this case). The vertical lines of the spectrum are the sideband frequency components, and are spaced apart by the pulse repetition frequency, f_r. The vertical lines are called spectral lines. In order for the spectrum analyzer to show the spectral line structure of the spectrum, the resolution of the analyzer must be smaller than the pulse repetition frequency.

However the spectrum envelope may still be resolved even if the spectral lines cannot be separated.

With the assumed pulse width of 10^{-8} seconds the distance between minima would be $2 \times 1/\tau = 200$ mc. In addition because of random variation of pulse amplitudes and the limitations of the spectrum analyzer to pass such narrow pulses undistorted, the spectrum envelope would not have sharply defined points of minimum and maximum that go to zero. A frequency dispersion of 10 mc was used in these photographs. Therefore the lobe structure of the frequency spectrum envelope would not be observable. On tuning the analyzer through a wide frequency range there were some indications of maximum and minimum points. However these indications could be a combination of lobe structure or resonance effects in the ignition system. (For example see chart 11).

For adequate resolution of the envelope of a pulse spectrum Polarad Electronics Corporation has stated in one of their handbooks (34) that the resolving power (R) should be smaller than one-tenth the reciprocal of the pulse length.

$$R \leq \frac{0.1}{\tau}$$

For pulses of width 10^{-8} seconds these give a desired resolution bandwidth of 10 mc or less which is easily obtained. A resolution of 2 kc was used which was the minimum for the SA84W analyzer. However since the pulse repetition frequency is much lower than the minimum resolution obtainable the spectral line structure can not be shown. The amount of detail

in the spectrum is also a function of the pulse repetition frequency and the analyzer sweep frequency. If the pulse repetition frequency is low and using a high sweep frequency the spectrum will appear only as vertical spikes. Each vertical spike represents a pulse received at the input. The total number of spikes on the analyzer scope equals the number of pulses received during the sweep time interval.

$$N = T \times f_r$$

where; T = sweep time interval (seconds)

f_r = pulse repetition frequency (pulses/second)

N = number of spikes

Polarad has recommended that for adequate definition of the spectrum shape that there should be 50 or more spikes on the screen. For the ignition system used here, f_r = 133 pulses/sec., and using N = 50, then T = 50/133 = 0.375 seconds (maximum). The slowest sweep time interval for the SA84W was one second, thus the number of spikes per one sweep would be approximately 133. Because of the slow sweep rate, it required photographing the screen during one sweep to obtain a complete representation of the frequency band under observation. Since only six spark plugs were used this resulted in six spikes and then two blanks. This can be noted most readily on the photographs for resistive leads. For regular leads the radiation from point openings on the two blank plugs may have resulted in radiation which partially filled in the blank spaces.

Figs. 3 through 17 show the variations in amplitude for each frequency and type of leads. The amount of I.F. attenuation in the spectrum analyzer

listed under each photograph must be taken into account when comparing values between photographs Also they show the wide random variation in amplitude for each plug within any set of six consecutive firings. A related observation was noted in analyzing waveforms on the oscilloscope. The plug being observed would have many firings giving very similar waveforms on the scope. However, every 10 or 20 firings the wave form would be quite different with several times the length of high frequency oscillations indicating very high voltages with repeated spark discharges. Thus these particular firings would result in a higher amplitude for that spark plug on the spectrum analyzer. Reduction of these very large amplitudes and obtaining (in some manner) uniformity of spark discharges would reduce the peak interference level by 6 to 10 db.

A factor which could also affect the amplitude distribution on the spectrum analyzer is that they may be occurring at a resonant frequency of the ignition system. This effect would tend to raise all amplitudes near that frequency by an amount proportional to the resonance response curve of the ignition system. Some photographs appear to show these resonance peaks. However, further investigation would be necessary to determine if this is the cause of the uniform increase of amplitudes for certain portions of the frequency spectrum. Increasing the frequency dispersion of the analyzer and repeated photographs of the same frequency band would give sufficient samples to permit a statistical analysis of this problem.

The following conclusions are made on the screen room interference measurements and spectrum analyzer results:

1. The frequency spectrum of the ignition system under analysis is very wide and with regular leads extends at least from 150 kc to 10 kmc.

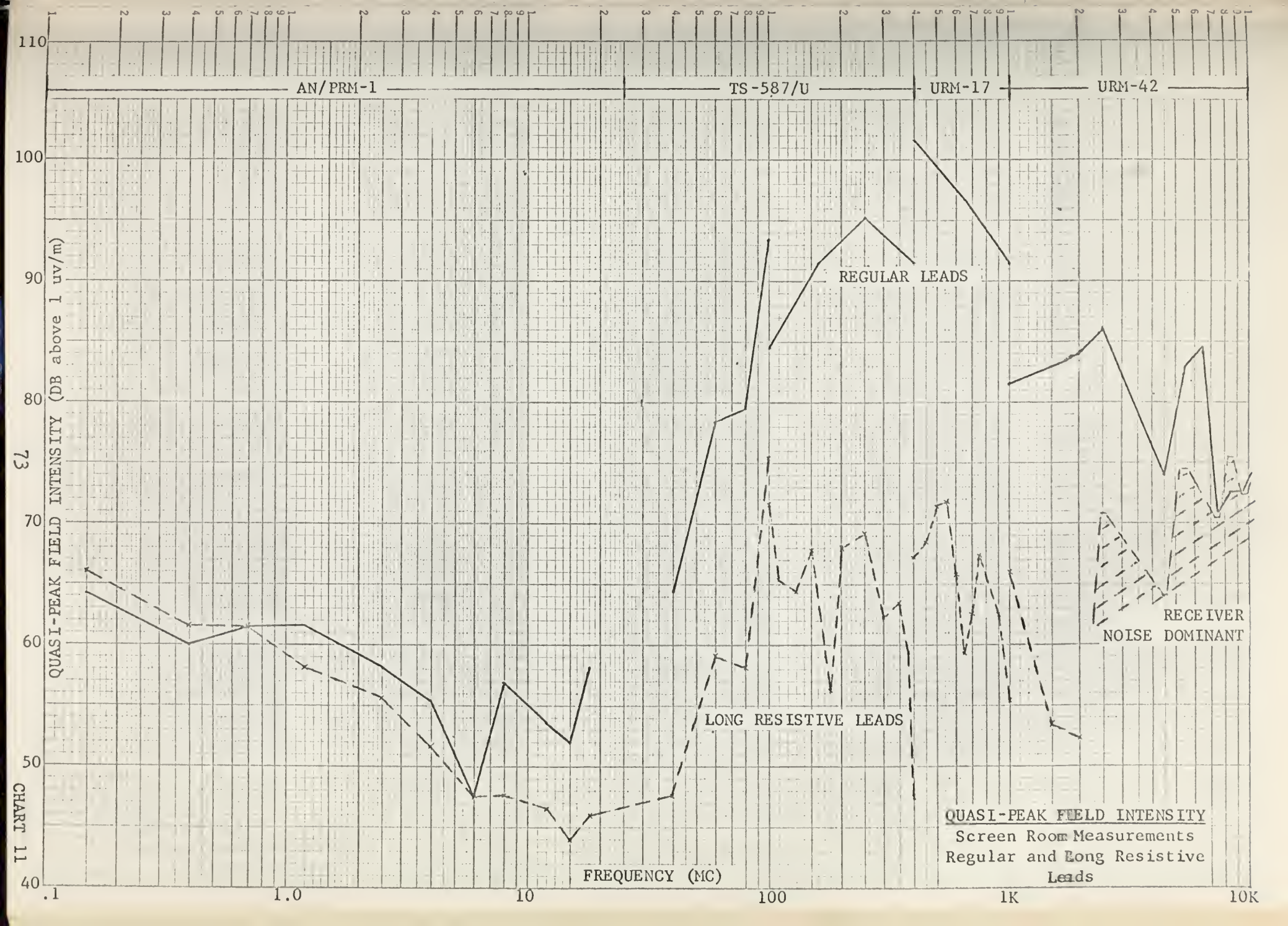
2. The frequency spectrum for peak values with resistive leads also extends from 150 kc to 10 kmc. For quasi-peak values the interference level stopped at approximately 2 kmc with ambient noise (including receiver noise) becoming the dominant factor.

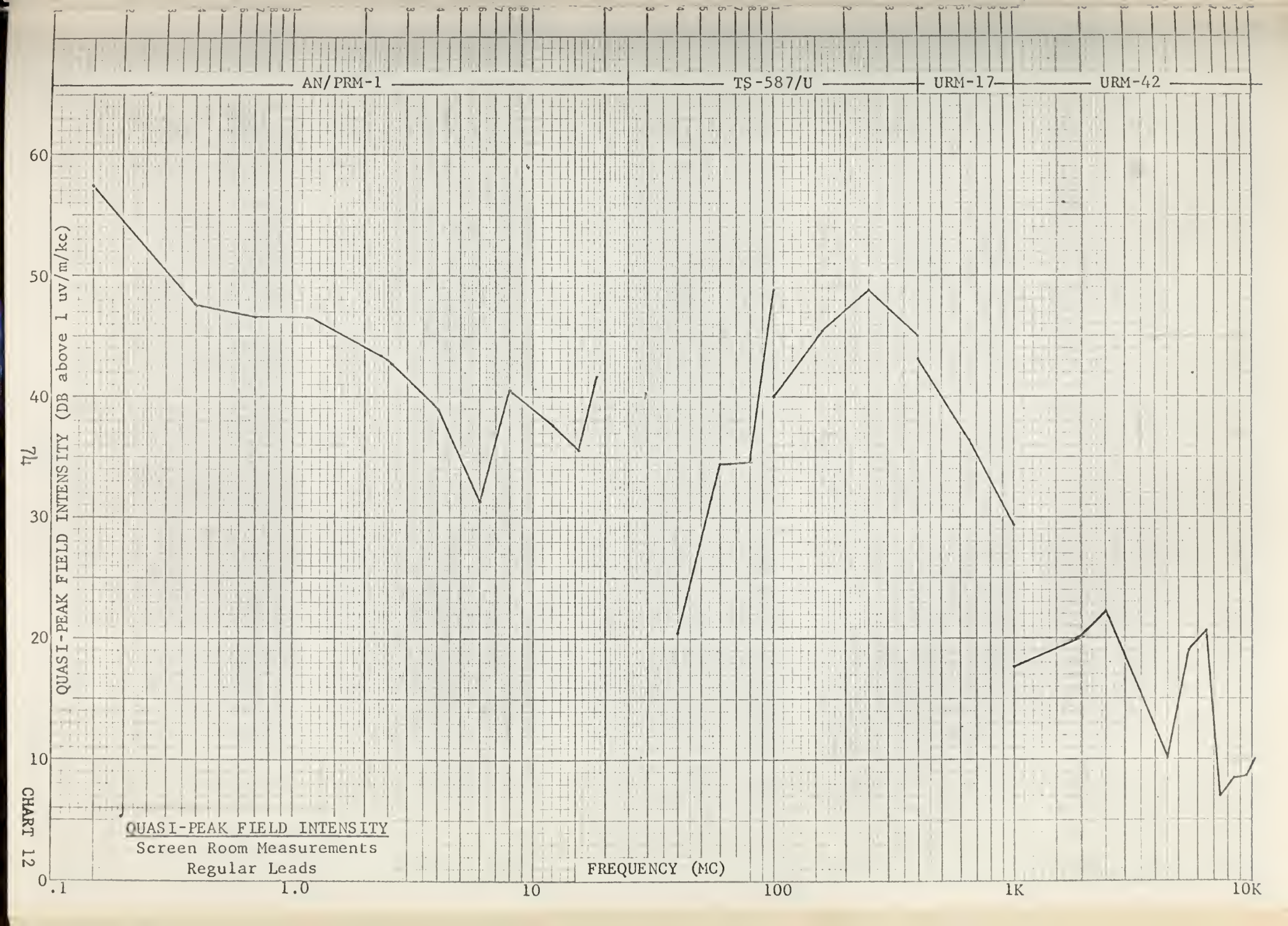
3. For frequencies above 10 mc the maximum peak interference levels with regular leads was approximately 72 uv/m/kc shown on chart 16 and 55 uv/m/kc for resistive leads shown on chart 17. Below 10 mc the peaks were approximately equal for both resistive and regular leads and equal to 73-74 uv/m/kc.

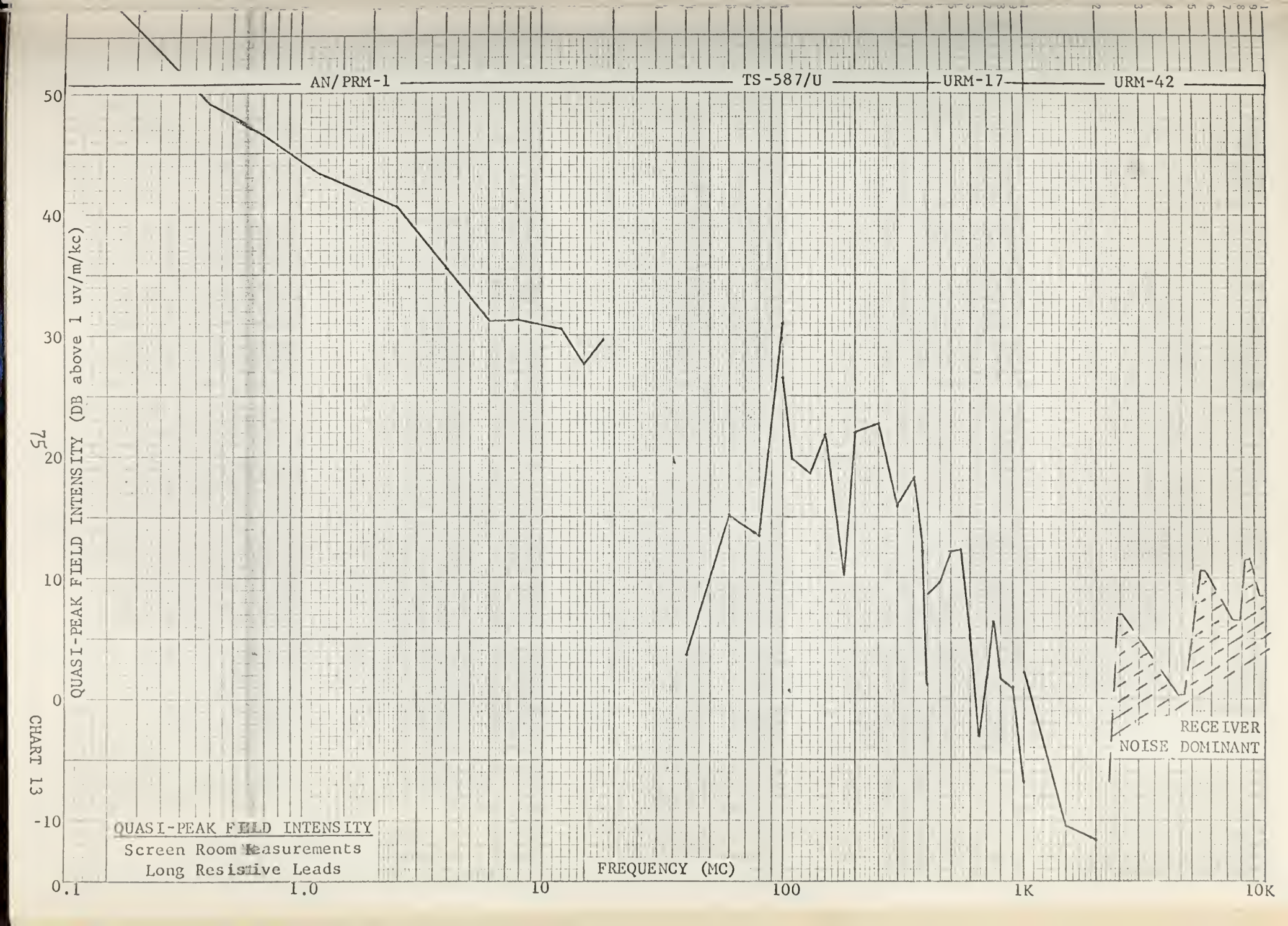
4. Resistive leads give approximately 20 db reduction of interference level compared with regular leads for frequencies above about 20 mc. Below these frequencies the two types of leads are very close in suppression characteristics. See charts 11 and 15.

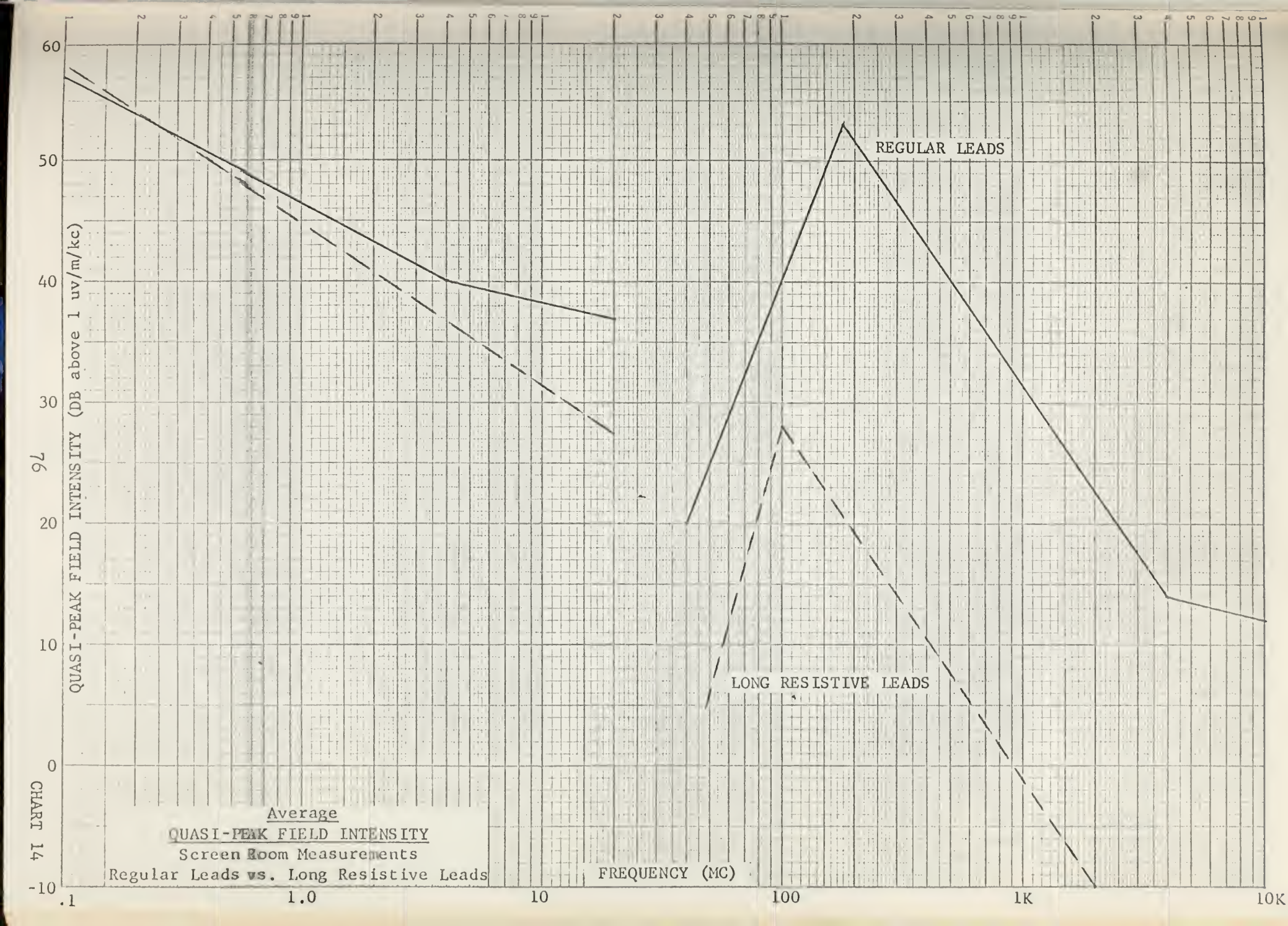
5. Crossover of interference levels for regular and resistive leads at approximately 0.8 mc is seen on charts 11 and 15. This tends to confirm the observations of Teachman (11) on an aircraft ignition system, but which he attributed at that time to a nearby transmitter. However, these screen room measurements show that the two types of leads tend to interchange their suppression characteristics at these low frequencies.

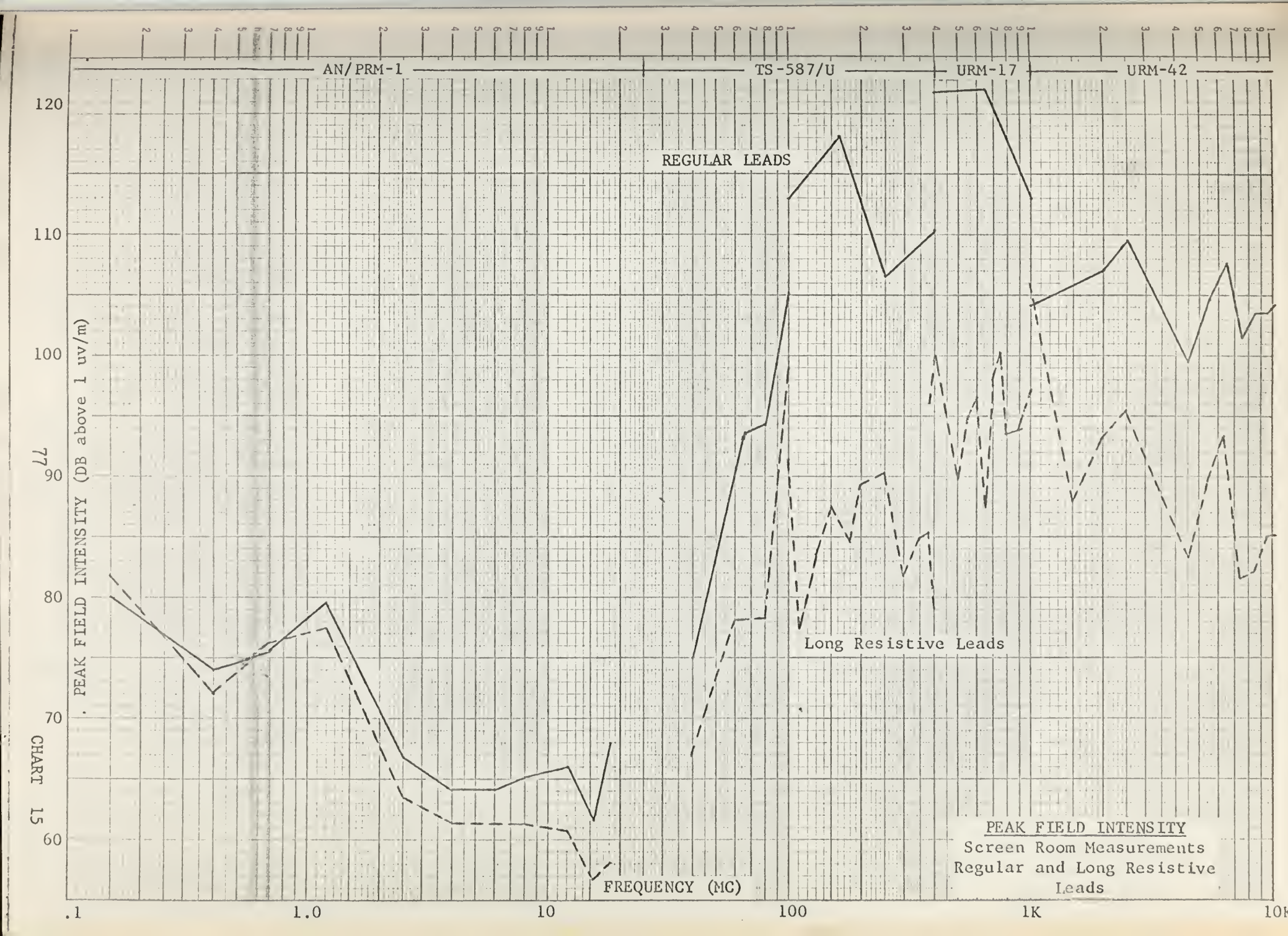
6. Amount of interference radiated from each spark plug firing vary randomly and may give values 6 to 10 db higher than the average plug firing.

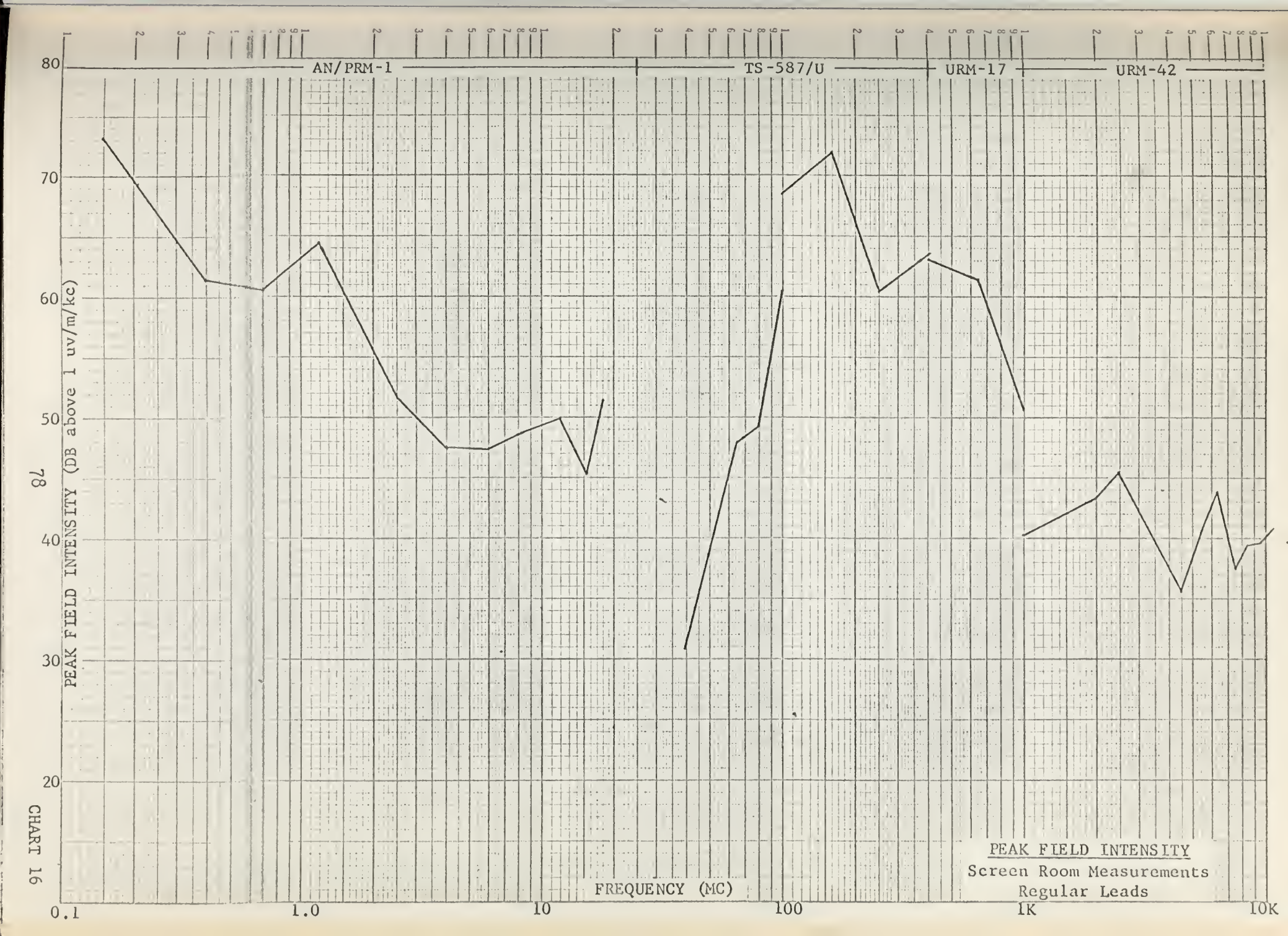

AN/PRM-1
TS-587/U
URM-17
URM-42
110
100
90
80
70
60
50
40
QUASI-PEAK FIELD INTENSITY (DB above 1 uv/m)
REGULAR LEADS
LONG RESISTIVE LEADS
RECEIVER
NOISE DOMINANT
.1
1.0
10
100
1K
10K
FREQUENCY (MC)
QUASI-PEAK FIELD INTENSITY
Screen Room Measurements
Regular and Long Resistive
Leads
CHART 11


AN/PRM-1
TS-587/U
URM-17
URM-42
QUASI-PEAK FIELD INTENSITY (DB above 1 uv/m/kc)
60
50
40
30
20
10
0
.1
1.0
10
100
1K
10K
FREQUENCY (MC)
QUASI-PEAK FIELD INTENSITY
Screen Room Measurements
Regular Leads
CHART 12
74


AN/PRM-1
TS-587/U
URM-17
URM-42
50
40
30
20
10
0
-10
QUASI-PEAK FIELD INTENSITY (DB above 1 uv/m/kc)
75
CHART 13
QUASI-PEAK FIELD INTENSITY
Screen Room Measurements
Long Resistive Leads
0.1
1.0
10
100
1K
10K
FREQUENCY (MC)
RECEIVER
NOISE DOMINANT

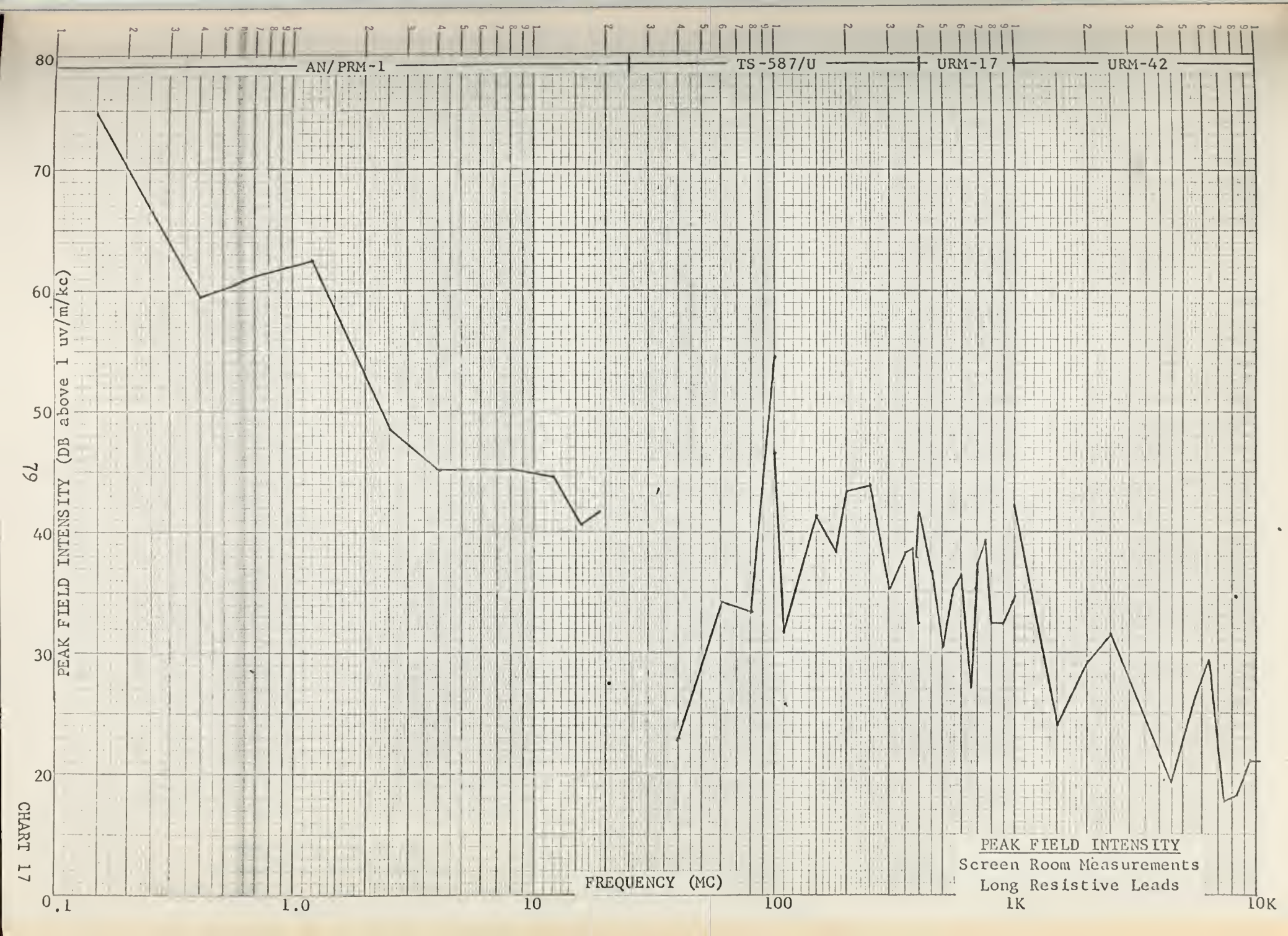

60
50
40
30
20
10
0
-10
QUASI-PEAK FIELD INTENSITY (DB above 1 uv/m/kc)
REGULAR LEADS
LONG RESISTIVE LEADS
.1
1.0
10
100
1K
10K
FREQUENCY (MC)
Average
QUASI-PEAK FIELD INTENSITY
Screen Room Measurements
Regular Leads vs. Long Resistive Leads
CHART 14
76

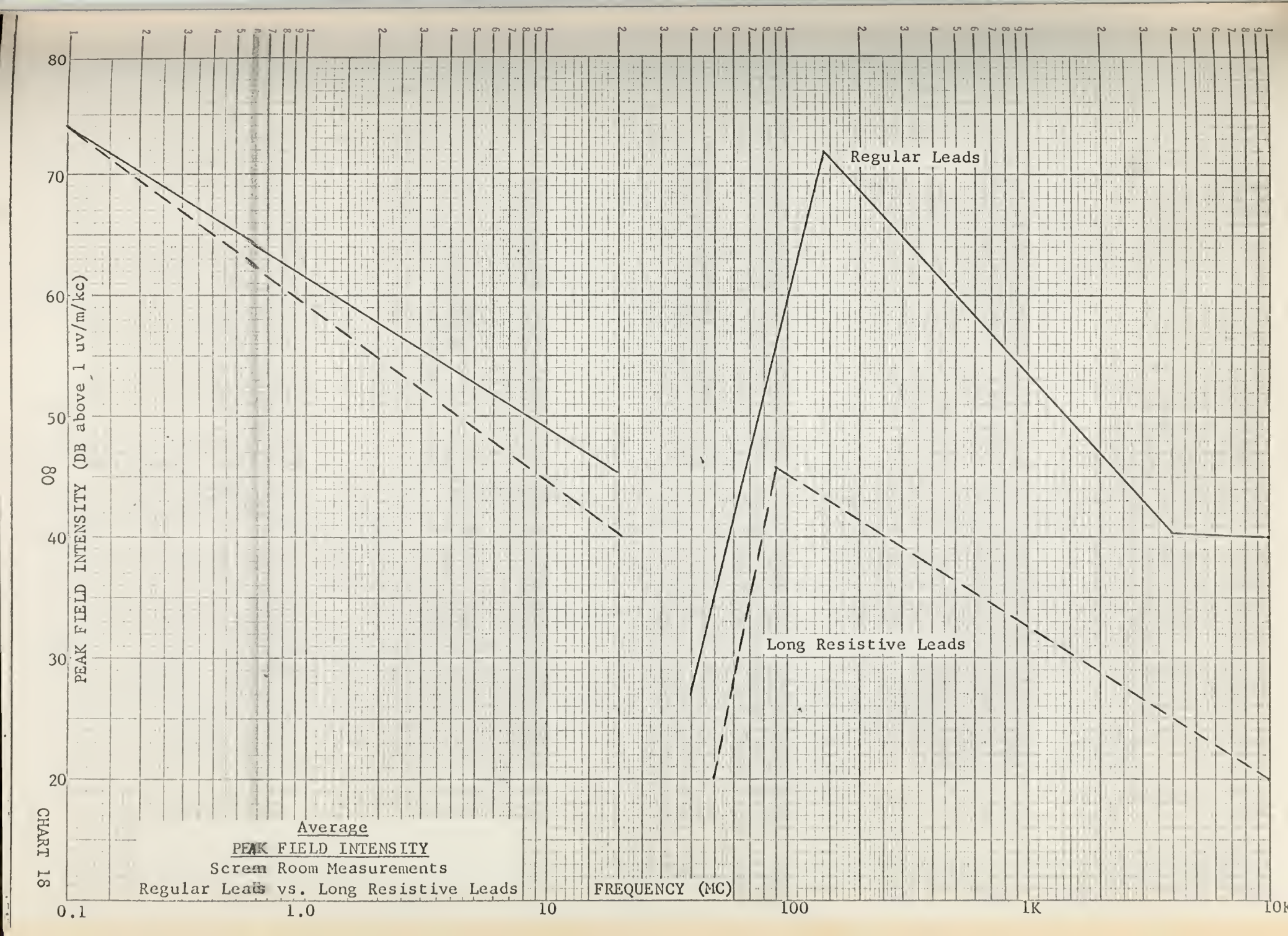

AN/PRM-1
TS-587/U
URM-17
URM-42
120
110
100
90
80
70
60
PEAK FIELD INTENSITY (DB above 1 uv/m)
REGULAR LEADS
Long Resistive Leads
FREQUENCY (MC)
.1
1.0
10
100
1K
10K
PEAK FIELD INTENSITY
Screen Room Measurements
Regular and Long Resistive
Leads
CHART 15

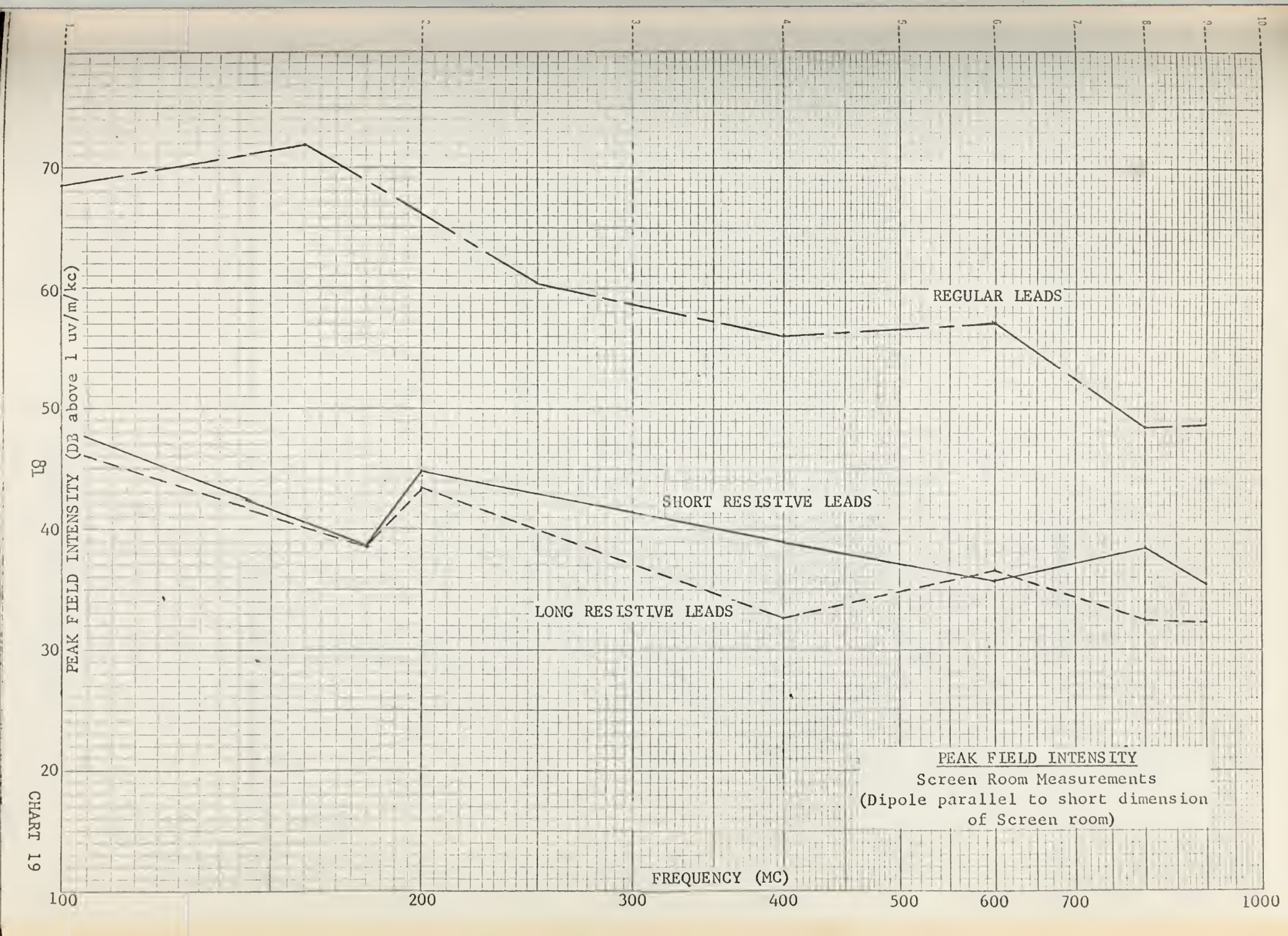

AN/PRM-1
TS-587/U
URM-17
URM-42
80
70
60
50
40
30
20
PEAK FIELD INTENSITY (DB above 1 uv/m/kc)
0.1
1.0
10
100
1K
10K
FREQUENCY (MC)
PEAK FIELD INTENSITY
Screen Room Measurements
Regular Leads

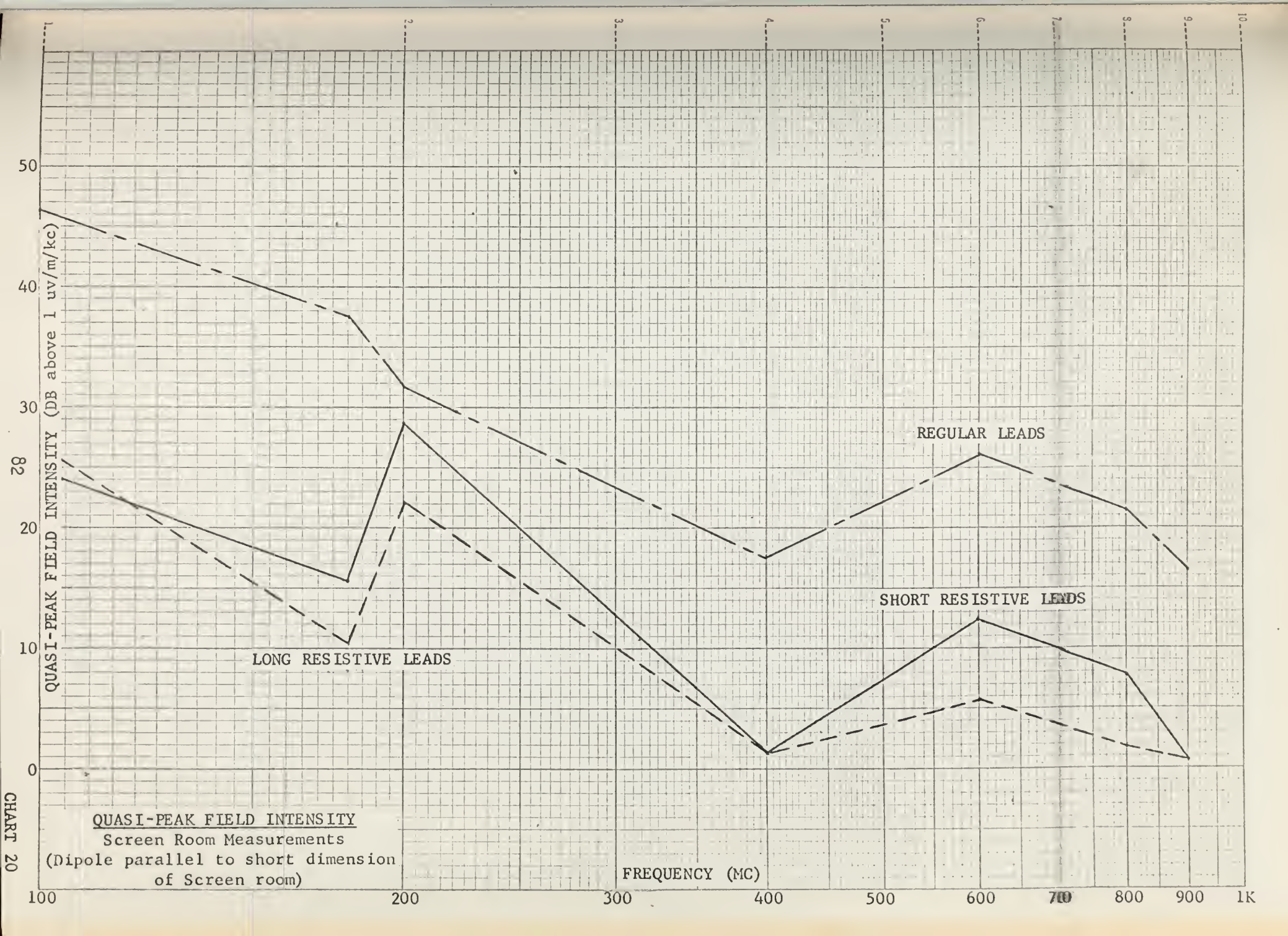
78

CHART 16


AN/PRM-1
TS-587/U
URM-17
URM-42
80
70
60
50
40
30
20
0
PEAK FIELD INTENSITY (DB above 1 uv/m/kc)
.1
1.0
10
100
1K
10K
FREQUENCY (MC)
PEAK FIELD INTENSITY
Screen Room Measurements
Long Resistive Leads
CHART 17

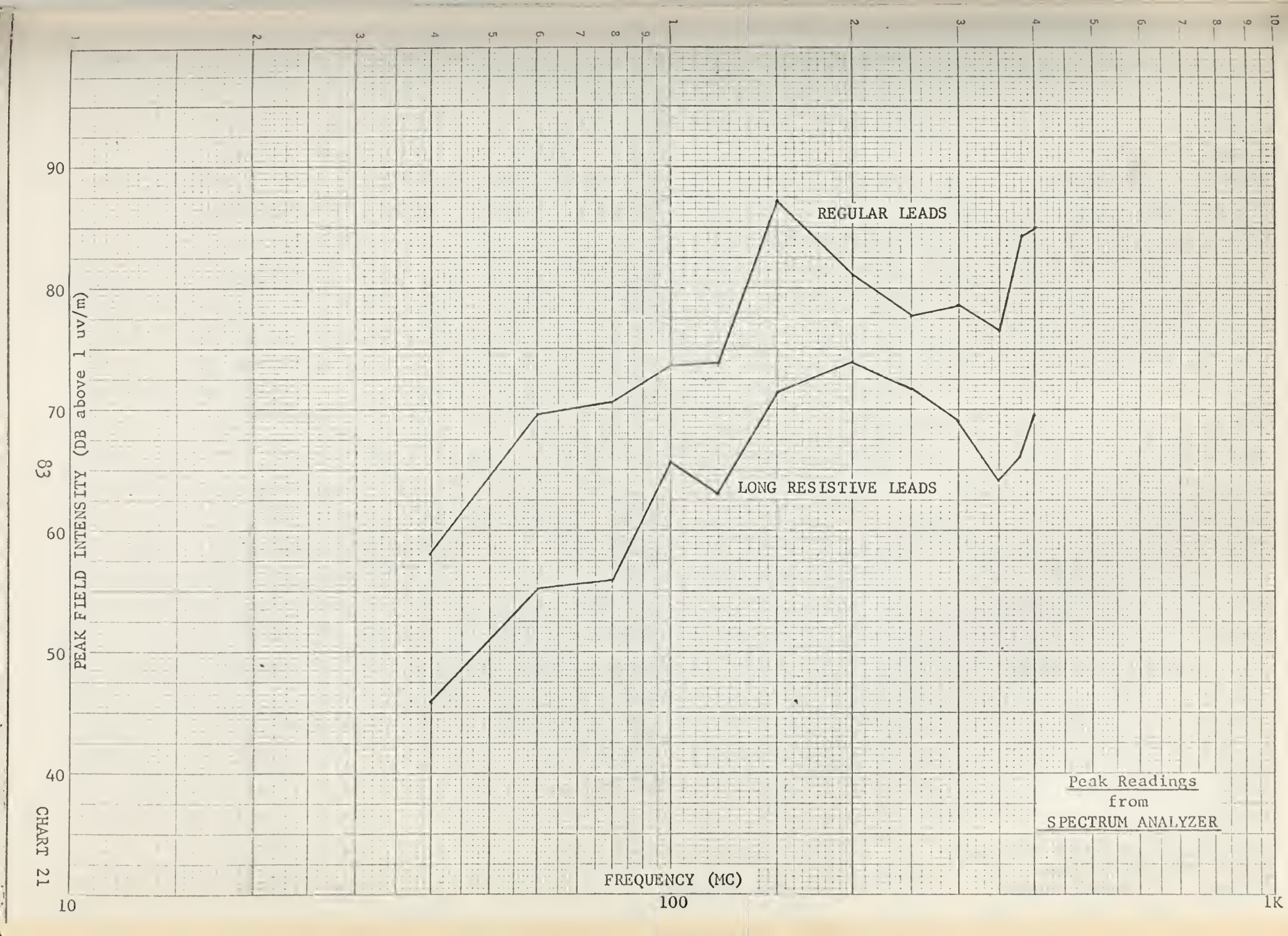

80
70
60
50
40
30
20
PEAK FIELD INTENSITY (DB above 1 uv/m/kc)
Regular Leads
Long Resistive Leads
0.1
1.0
10
100
1K
10K
FREQUENCY (MC)
Average
PEAK FIELD INTENSITY
Screm Room Measurements
Regular Leads vs. Long Resistive Leads
CHART 18


PEAK FIELD INTENSITY (DB above 1 uv/m/kc)
DB
70
60
50
40
30
20
REGULAR LEADS
SHORT RESISTIVE LEADS
LONG RESISTIVE LEADS
PEAK FIELD INTENSITY
Screen Room Measurements
(Dipole parallel to short dimension
of Screen room)
FREQUENCY (MC)
100
200
300
400
500
600
700
1000
CHART 19



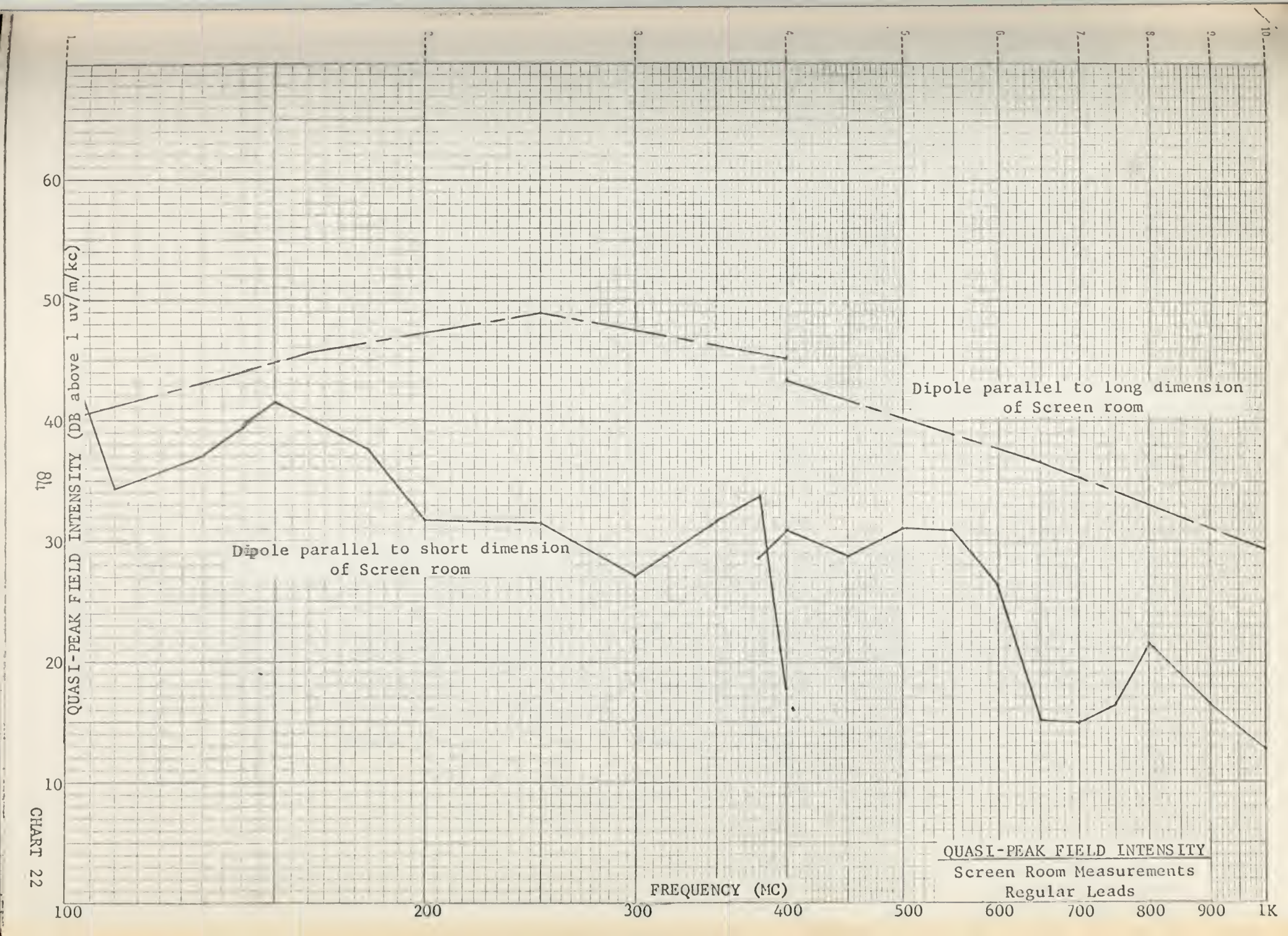
QUASI-PEAK FIELD INTENSITY
Screen Room Measurements
(Dipole parallel to short dimension of Screen room)

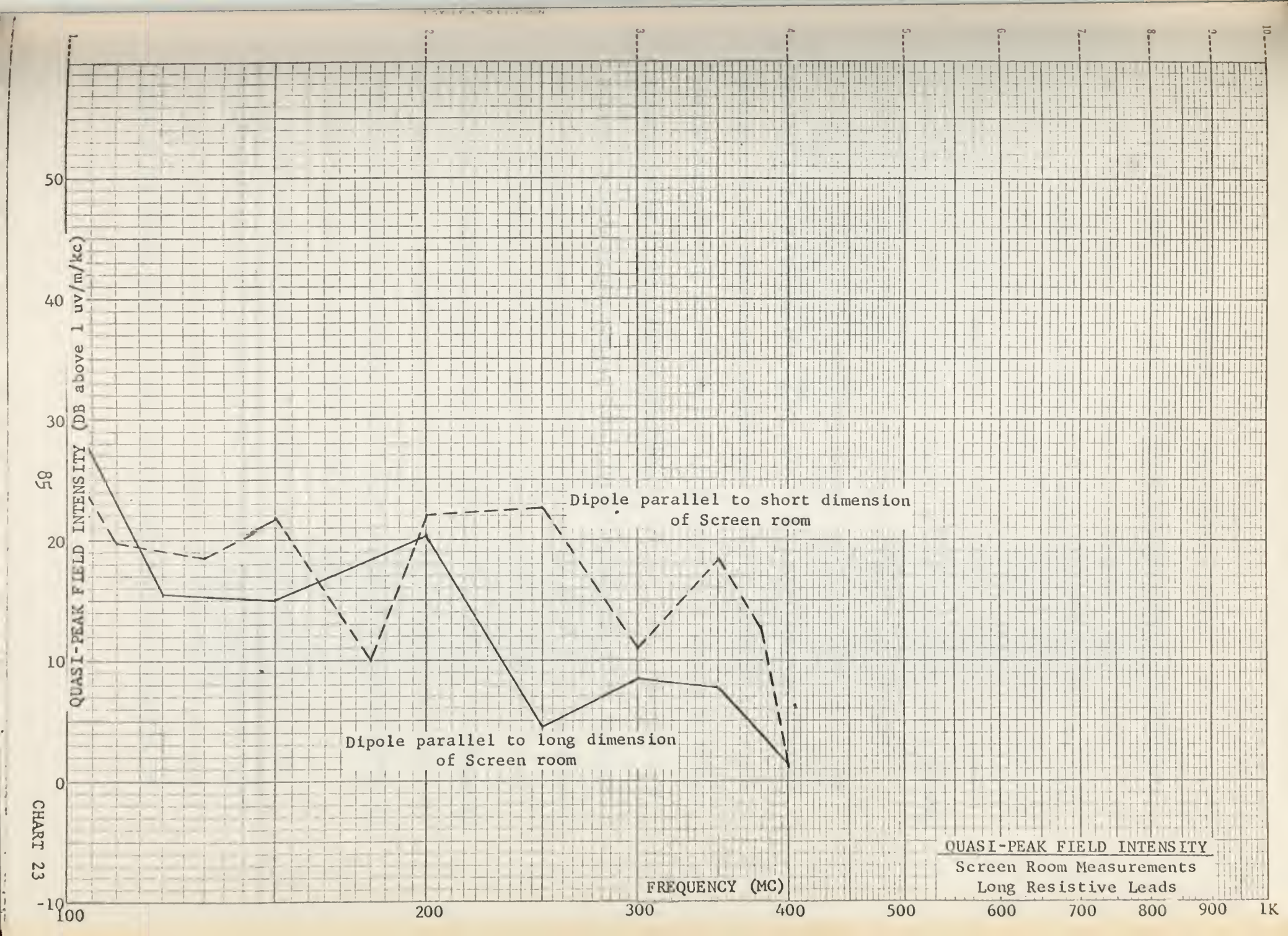
CHART 20


PEAK FIELD INTENSITY (DB above 1 uv/m)
90
80
70
60
50
40
REGULAR LEADS
LONG RESISTIVE LEADS
Peak Readings
from
SPECTRUM ANALYZER
FREQUENCY (MC)
10
100
1K

83

CHART 21


QUASI-PEAK FIELD INTENSITY (DB above 1 uv/m/kc)
60
50
40
30
20
10
Dipole parallel to long dimension of Screen room
Dipole parallel to short dimension of Screen room
FREQUENCY (MC)
100
200
300
400
500
600
700
800
900
1K
QUASI-PEAK FIELD INTENSITY
Screen Room Measurements
Regular Leads
CHART 22


QUASI-PEAK FIELD INTENSITY (DB above 1 uv/m/kc)
50
40
30
20
10
0
-10
Dipole parallel to short dimension of Screen room
Dipole parallel to long dimension of Screen room
100
200
300
400
500
600
700
800
900
1K
FREQUENCY (MC)
QUASI-PEAK FIELD INTENSITY
Screen Room Measurements
Long Resistive Leads
85
CHART 23

7. High Tension Current Waveforms in an Ignition System.

To gain some insight into the cause of ignition radiated interference, an investigation was made of the current waveform in the high tension circuit. To perform the investigation, a mockup ignition system was used with the distributor running at approximately 1,000 rpm and the current was sampled on the ground side of one of the spark plugs. Current was chosen for examination rather than voltage since it is directly related to the radiated interference through the radiation resistance of the effective antenna.

To accomplish this current measurement, one of the spark plugs was mounted in a bracket insulated from ground and the bracket was grounded through a 10 ohm composition resistor (see Fig. 1). Although the current in the high tension lead on the high side of the spark plug appears to be more directly related to the radiated interference, difficulty was encountered in attempts to measure the current there. Whenever the scope was connected to put its ground reference on the high tension side of the plug, the capacity of the ground circuit of the oscilloscope was such that it prevented a sufficient voltage buildup to fire the plug. Although this current is not accurately representative of current in the high tension leads because of reflection and transmission losses in the plug, it is a good indication of radiation-causing currents flowing on the high tension side of the plug.

In measuring the current, the voltage developed across the 10 ohm sampling resistor was displayed using the upper beam of a Tektronix model 555 oscilloscope (see Appendix C for specifications) with a 10X attenuator probe as the pickup device. Since the waveform was non-repetitive, the

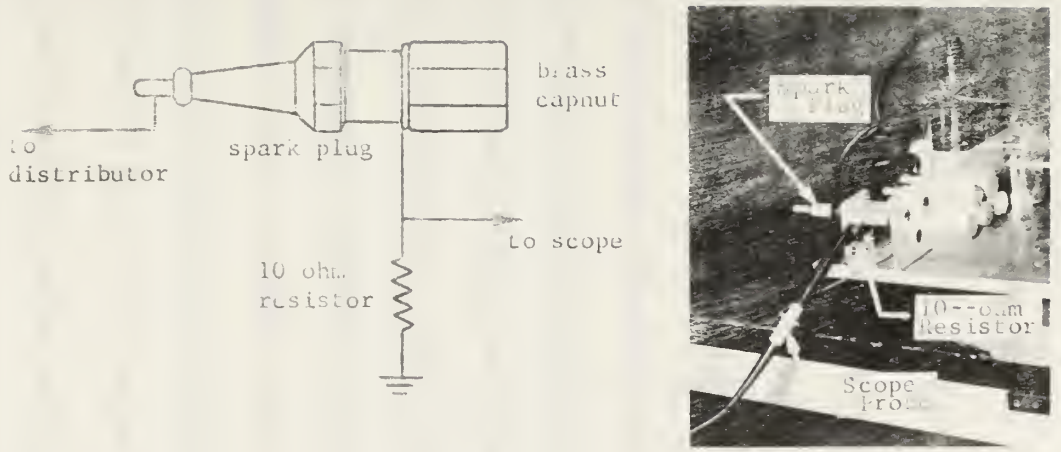


FIGURE 1

Schematic representation and photograph of arrangement for measuring spark plug current waveforms.

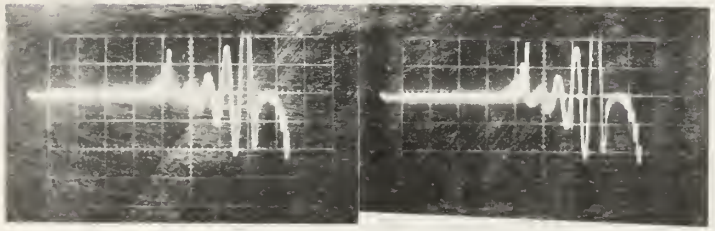


FIGURE 2

Probe Pickup
Horizontal Scale 0.5 millisec./cm.

FIGURE 3

Probe Pickup
Horizontal Scale 1.0 millisec./cm.

single sweep feature of the scope was used for photographing the display. The scope displays were recorded on polaroid (Land) film of various speeds (ASA 400, 3,000, 10,000) depending on the sweep speed, using time exposures to take advantage of the residual brightness. Although some of the waveform characteristics near the instant of firing do not show in the photographs because of the brightness limitations on rapid waveform changes at high sweep speeds, some of the features were observed visually over several seconds by triggering the sweep on every firing. These characteristics are mentioned in the discussion of the waveform photos.

During the investigation, two factors were noted which contribute to the spectrum width of the interference. Rather than trigger the scope sweep on the waveform being examined which prevented accurate examination of the beginning of the waveform, an attempt was made to trigger the sweep with the firing of the previous plug, on the assumption that the short time variation in mechanical frequency of the system would be negligible. A one-shot multivibrator with a variable delay was used to start the sweep just before the firing of the plug under observation. For relatively low sweep speeds (greater than 10 usec./cm), the waveform was stable in position on the scope; but for sweep speeds necessary to observe the detail of the wavefront (on the order of 0.1 usec./cm), it was difficult to keep the trace of the waveform in the display range. This jitter or evidence of variation in the time between firing of two adjacent plugs was as much as one microsecond and more from one revolution to another. Although this variation is very small compared to the average time between firing of adjacent plugs

(approx. 7.5 millisec.), it is a contributing factor in building up continuity of the spectrum since one of the basic periodicities has some randomness. This inconstancy has been attributed to frequency of rotation variation with each revolution. However, other phenomena such as delay in formation of the wavefront due to contact arcing during opening, variation of breakdown voltage depending on points of termination of the spark, and statistical randomness in initiating the spark once breakdown voltage has been achieved, may have contributed to this variation. Since the mockup ignition system was driven with an electric induction motor through a fluid coupling with inherent smoothing, it is expected that the variation in each revolution of the firing of adjacent plugs in an automobile engine would be considerably higher, and even this entire effect may be dwarfed by the variation in rpm expected from any automobile, even at "constant" speed. The second factor noted was a few per cent variation in the time the points remain open on each lobe during the revolution. This is undoubtedly caused by undesired eccentricities in the cam, or radial play in the shaft on which the cam is mounted, and may have been a characteristic only of the particular distributor used. In any event, since radiation is initiated upon point opening and closing, the effect of this variation is also to widen and contribute continuity to the frequency spectrum.

Figs. 4 through 8 are single sweep photographs of the sampled current on the low voltage side of one spark plug. The photos all display the initial portion of the current waveform and are arranged to successively show increasing detail of this portion of the current. The major divisions on the

scope graticule represent centimeter squares. The lowest 1-1/2 centimeters of the graticule are out of range of the upper beam of the scope and any portion of the waveform extending into that area is cut off. The sweep is from right to left in all photos.

Fig. 4 shows the total period of detectable current flow through the sampling resistor. The total time from initial breakdown to quenching is about 0.68 milliseconds. The peaks noticeable near the beginning of sweep are about 0.64 volts and decay in the form of a damped low frequency (15 kc) sine wave superimposed on an "exponential type" decay curve. The quenching is rather abrupt and may be caused by stretching of the arc to the break point in the gap between rotor and distributor cap terminal.

Fig. 5 expands the first portion of Fig. 4 by a factor of five. The initial peaks can be seen in greater detail and the high frequencies near the beginning of sweep become evident. About 35 microseconds after firing, the current approaches the damped 15 kc oscillation noted in Fig. 4.

Fig. 6 displays the first portion of Fig. 5 magnified by a factor of four so that one centimeter now represents 5 microseconds. The first portion of the wave can be seen to contain rapidly varying high frequency components and approximately a 1.2 mc ripple can be seen on the more slowly varying components after the first 1.5 microseconds. The zero level is at the top graticule line and the sweep begins one centimeter from the right edge of the graticule.

Fig. 7 is an expansion of the first 2 cms (10 microseconds) of sweep in Fig. 6. The 1.2 mc ripple can be seen more clearly and high frequency

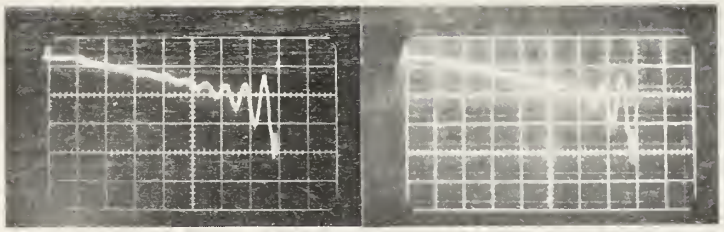


FIGURE 4

Horizontal Scale 100 μsec./cm.
Vertical Scale 0.2 volts/cm.

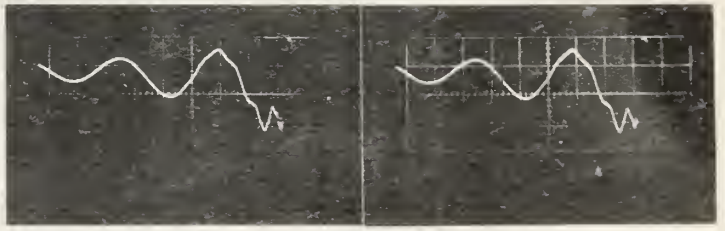


FIGURE 5

Horizontal Scale 20 μsec./cm.
Vertical Scale 0.2 volts/cm.

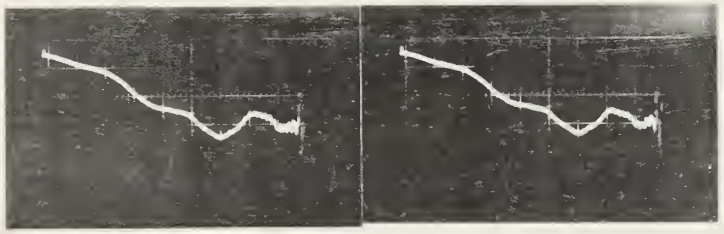


FIGURE 6

Horizontal Scale 5 μsec./cm.
Vertical Scale 0.2 volts/cm.

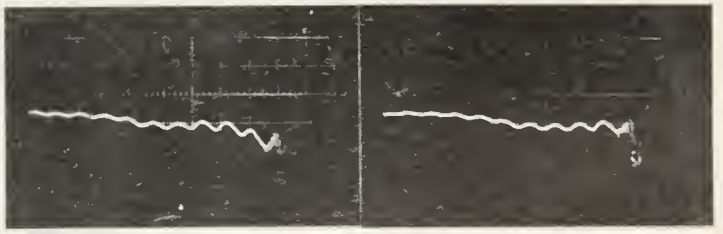


FIGURE 7

Horizontal Scale 1 μsec./cm.
Vertical Scale 0.2 volts/cm.

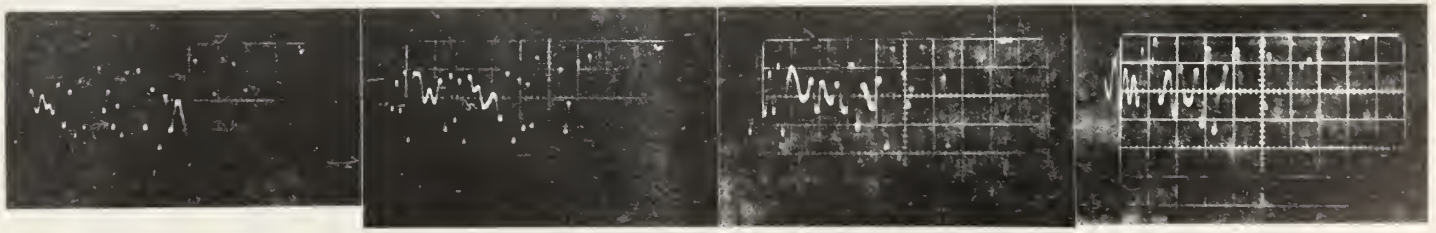


FIGURE 8

Horizontal Scale 0.1 μsec./cm.
Vertical Scale 0.5 volts/cm.

components nearer the time of firing are more evident.

Fig. 8 shows the high frequency oscillations encountered in the first microsecond of sweep. A few cycles of 20 mc and 30 mc oscillations are evident along with a complex envelope and sudden changes of phase on these more basic frequencies. Note that the vertical scale now represents 0.5 volts/cm. Many of the oscillations near the beginning of sweep were off the range of the screen at this sensitivity. Although the first portion of the sweep is not visible in the photograph, observation of several sweeps showed it to contain oscillations of much greater magnitude of approximately the same frequency.

Since all the photos above were obtained by triggering the scope sweep with the input signal, the form of the current at its onset could not be observed in detail. However it was noted that oscillations of the 20-30 mc rate did not begin with the initiation of sweep but usually followed a brief period of perhaps 50 nanoseconds of little or no scope deflection. It is assumed that this sequence of events is brought about by a current pulse of extremely short duration (but possibly very large magnitude) which triggers the sweep, followed by a period of very high frequency oscillations well beyond the bandpass limitations of the scope to account for the period of little deflection. An abrupt change of oscillatory frequency to the 20-30 mc rate then causes the appearance of significant deflection at this frequency range.

Several considerations indicate that this is not an unreasonable explanation. The triggering level was set at a relatively high level so the

sweep would not trigger on pickup from extraneous signals. The basic oscillatory frequencies visible in the waveform after the first half microsecond do not change frequency in a gradual fashion but seem to undergo relatively abrupt changes over the period of spark plug current. As shown in Figs. 4 through 8, the basic oscillation frequency near the end of the spark current is about 15 kc; but as the instant of firing is approached, the frequency jumps abruptly to approximately 1.2 mc, and then again to 20-30 mc. At these high frequencies, the bandpass characteristic of the scope is very steep, and if an abrupt change to a much higher frequency takes place, it must overcome 60 or more db of discrimination to compare with the response at about 1 mc. Although the basic bandpass of the scope is from 0 to 30 mc, all measurements were made with a Tektronix 53B wide band plug-in preamp which narrowed this considerably. The bandpass characteristic of the combination of scope and plug-in was measured at the vertical sensitivities at which all photos were taken and is included in Appendix C. Therefore, the assumption of a very high oscillatory frequency not followed by the scope near the instant of spark firing is not unreasonable.

Figs. 2 and 3 are probe pickup obtained by holding the scope attenuator probe about a foot from the wiring harness of the distributor. The first portion of the waveform in Fig. 2 represents the spark current discussed above, while the remainder of the pickup waveform (the large damped 3 kc sine wave and the damped offset sine wave of about 13 kc following, due to points closing) is confined to circuits on the high tension side of the plug. The source of this radiated pickup is principally the high tension lead from

coil to distributor and magnitude of the waveform fell off rapidly as the probe was moved away from that lead. Note the sharp breaks in the waveform as it changes frequency at the cutoff of spark current and then again when the points close.

The waveform of the spark current displays a wide range of frequency components. It appears to contain discrete oscillatory frequencies, or discrete narrow bands of oscillatory frequencies, changing from one frequency or band to another very abruptly as a function of time. The highest oscillatory frequencies occur just after breakdown and drop to successively lower frequencies as time increases. The oscillatory frequencies themselves are modulated with some complex waveform which contributes many other frequency components to the total current.

The current in the high tension lead which connects coil to distributor cap appears to be the most profuse radiator. However, after the spark current has terminated, there is no oscillatory radiation above about 13 kc. Harmonic content of the radiation after spark termination would primarily be caused by the sudden breaks in the waveform when the frequencies change.

8. Interference Criteria and Standards.

For an effective program of interference reduction it is necessary to have standard interference criteria and limits. However these standards and limits must be realistic and have uniformity to gain acceptance by industry and other groups concerned.

Many European countries have done considerable research in the field of interference reduction and the establishment of standards. Many of the recent published papers on ignition systems have been by European laboratories or companies. Therefore the various European standards and the draft of a proposed International standard submitted to CISPR (International Special Committee on Radio Interference) will be briefly reviewed.

One definition which has been given for interference is: "Undesired conducted or radiated electrical disturbances, including transients, within the range of frequencies covered by applicable specification, which may interfere with the operation of electronic equipment or communications" (28).

If perfect receivers existed, the absolute criterion for determining whether or not there were interference would be: "Is the ratio of desired signal greater than a predetermined level for having satisfactory performance of the system?" (34).

$$S_D/S_I = R_A$$

where, S_D = Desired signal, S_I = Interfering or undesired signal, and R_A = Predetermined ratio of acceptance, or threshold. This acceptance ratio is a factor which may assume many values depending on the type of signal modulation, intelligence content of the signal, type of receiver, nature of the

interfering signal or noise, signal coding or redundacy of the information, and other factors. The determination of this acceptance ratio sets the signal strength required in the presence of a certain interference level. If these interfering signals or sources were reduced in strength then signal strength required to complete a communication circuit would be correspondingly reduced. The ensuring result would be less cost of operation or longer ranges with the same power output.

Considerable engineering effort has gone into design of sensitive electronic equipment. However, this effort is often wasted because the equipment is operated in an environment which has a high level of interference such that it requires a strong signal to overcome the noise. In these cases a less sensitive piece of equipment would serve effectively and be less expensive. Proper utilization of very sensitive electronic equipment dictates operation in a low interference level environment (which may be difficult to find) or the prevailing level of interference must be reduced to a value below the lowest detectable desired signal. Pulse code systems of communication are particularly susceptible to sharp noise impulses or "noise burst" interference such as that radiated from ignition systems.

In determining interference criteria, there are three main elements in the establishment of an interference condition: (26)

a. Source of the interference.

b. Transmission or coupling path between source and point of interference.

c. Susceptible electronic equipment.

With the elimination of any of these three elements no interference condition would exist. Thus in attempting to operate an electronic system in an interfering environment there may be several courses of action available to reduce the interference. In addition interference standards and limits may vary depending on the problem or type of interference under consideration. Some of the following methods of combating interference and noise are used.

1. Elimination or reduction of the strength of the noise by taking action against the source.

2. Raising the signal to noise ratio by increasing the transmitted power.

3. Using special signal design or coding techniques.

4. Using directional antennas.

5. Design and production of interference-free equipment.

6. Proper installation and placement of equipment.

7. Reducing the susceptibility of receivers.

8. Using compatible equipment in system design

9. Proper operating and maintenance procedures.

10. Using, for impulsive disturbances reaching the receiver, (20)

    a. Non-linear saturating elements or noise clippers.

    b. Disturbance-triggered, gating-out schemes.

    c. Linear-cancellation techniques.

It is desirable from the long range viewpoint that interference be eliminated or reduced at the source. There would be many advantages to this approach. For example an undesired output in the form of noise or interfer-

ence from some man-made equipment usually represents the generation of unnecessary power with consequent reduction of the overall efficiency of the basic function of the equipment.

The Bureau of Ships, Department of the Navy, policy concerning the development and procurement of new equipment is:

a. Interference shall be minimized to such a degree as to prevent interference with naval communications or the malfunctioning of electronic equipment insofar as the state of the design art for each individual equipment or system permits such minimization. Specifications and instructions will reflect the state of the design art for individual equipment.

b. For economy, effectiveness, and reliability in service, interference reduction shall be accomplished in the initial design and the controlled manufacture of the various equipment. (28)

The pertinent specifications from MIL-I-16910A (SHIPS) are given in Appendix A. In the establishment of interference criteria and limits it is essential that uniform standards be followed in all tests. As noted in Section 5 the measurements taken at the three foot distance from the car were very sensitive to antenna location and car body configuration. Test conditions and test methods were in close accord with Section 4.5 of MIL-I-16910A (SHIPS).

Information on current European standards was obtained from an article by Egide and Nano (18). Features common to the standards of three European countries are that measurements of ignition interference be made at a site sufficiently large and free of obstacles and that the horizontal distance

between the car and antenna be at least 10 meters. The engine is run at a fixed speed in the French and German standards, while in the British standard it is accelerated rapidly from idling speed. At the end of 1957, the standards set an interference limit of 50 uv/m in Germany and the United Kingdom; in France, the limit was 30 uv/m but the car to antenna distance is approximately 14 meters compared to a 10 meter distance in the former case.

The draft of a proposed International standard for measuring ignition interference, and proposed limits which were given by Egidi and Nano (18) is reproduced in part in Appendix B.

This proposed standard is for frequencies below 225 mc and is based on measurements up to 400 mc. However, measurements of interference from a 1962 Chevrolet show a marked increase in peak values in the frequency range above 200 mc (charts 7 and 8). Also, if Figs. 1 and 3 of Pressey and Ashwell's report (12) are combined, the result shows the same increase of interference up to the frequency limit of their measurements (600 mc).

A comparison of measured values from chart 8 and the proposed interference limits are shown on chart 24. CISPR limits were converted to uv/m/kc by using the average bandwidth of the URM-47 which is the equivalent of the measuring set used by Egidi and Nano. Chart 24 shows that the measured interference exceeds a linear extension of the proposed limit above 250 mc. For further comparison the data of Pressey and Ashwell (12) corrected for insertion of resistive leads (taken from Figs. 1 and 3 of

their report and shown in Section 4 of this paper) is shown on Chart 25 with the same proposed Interference standard. When compared on the basis of uv/m the CISPR standard is below the measured interference levels of Pressey and Ashwell. The inability of production cars to meet the proposed standard indicates a need for further examination of ignition systems as well as the standard before the adoption of a standard is contemplated. In light of the extreme width of the ignition spectrum, further investigation should extend to at least 1000 mc and should include measurements on a sufficient number of production model American cars to obtain an appropriate statistical sample. Interference levels presently encountered and the economy factors to be dealt with in attempting to reduce such levels would demand special consideration in drafting a standard of permissible levels.

Comparison between screen room measurements with resistive leads and field measurements at three feet is shown on charts 26 and 27. These indicate suppression by the car body of frequencies from approximately 40 to 400 mcs. From 400 mcs to about 1000 mcs the two tests show comparable levels of interference. However, different types of cars and car bodies could very likely exhibit their strongest attenuation characteristics over other portions of the radiation spectrum.

Chart 26 also compares the measured peak interference levels at three feet with the broadband radiated interference limits given in MIL-I-16910A (Appendix A). The measured values are substantially above the limits and indicate the possible requirement for complete shielding of the ignition

system as shown in Section 3 in order to satisfy the specified limits. Such shielding is a common requirement for military vehicles near certain electronic facilities and other critical areas.

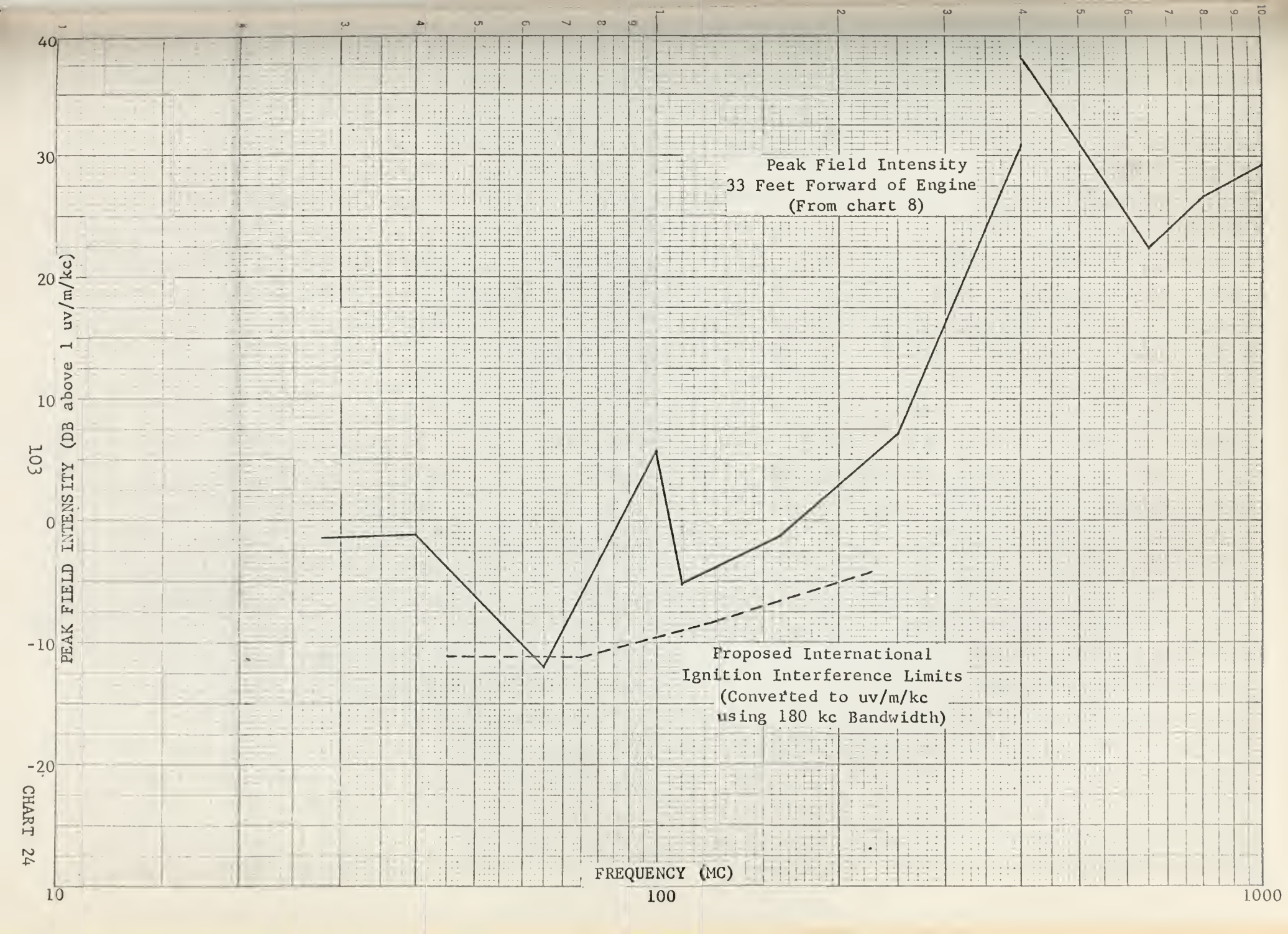
Tests of regular leads in comparison with resistive leads have verified that the radiation from almost any ignition system using regular leads can be substantially reduced by the substitution of resistive ignition leads. Therefore, any limits on radiated interference proposed for general public enforcement should be based on the reduced interference levels achieved through the use of resistive leads. Although most modern cars have resistive ignition leads, many buses and trucks do not and therefore contribute a significant amount of ignition interference.

The measurements made in connection with the preparation of this paper deal with only a small sample of the many and diverse sources of ignition interference, but were sufficient to emphasize the difficulties to be overcome in arriving at a reasonable standard. The establishment of such a standard would first require a wider range of investigation on modern cars to give statistically meaningful values for present levels of interference. Other factors which deserve consideration in forming a standard are:

1. Results of Egidi and Nano, Pressey and Ashwell, and other sources of information regarding existing interference levels.
2. Evidence of higher radiation levels in the 400 to 1000 mcs range.
3. Desirability of using uv/m/kc as the standard unit of interference to permit comparison of results determined by different equipments.

4. Limits which are consistent with the need for reduction in each frequency range taking account of usage and other problems such as atmospheric and receiver noise.

5 The cost of incorporating suppression required to satisfy proposed limits.


Peak Field Intensity
33 Feet Forward of Engine
(From chart 8)
Proposed International
Ignition Interference Limits
(Converted to uv/m/kc
using 180 kc Bandwidth)
PEAK FIELD INTENSITY (DB above 1 uv/m/kc)
40
30
20
10
0
-10
-20
FREQUENCY (MC)
10
100
1000
CHART 24
103

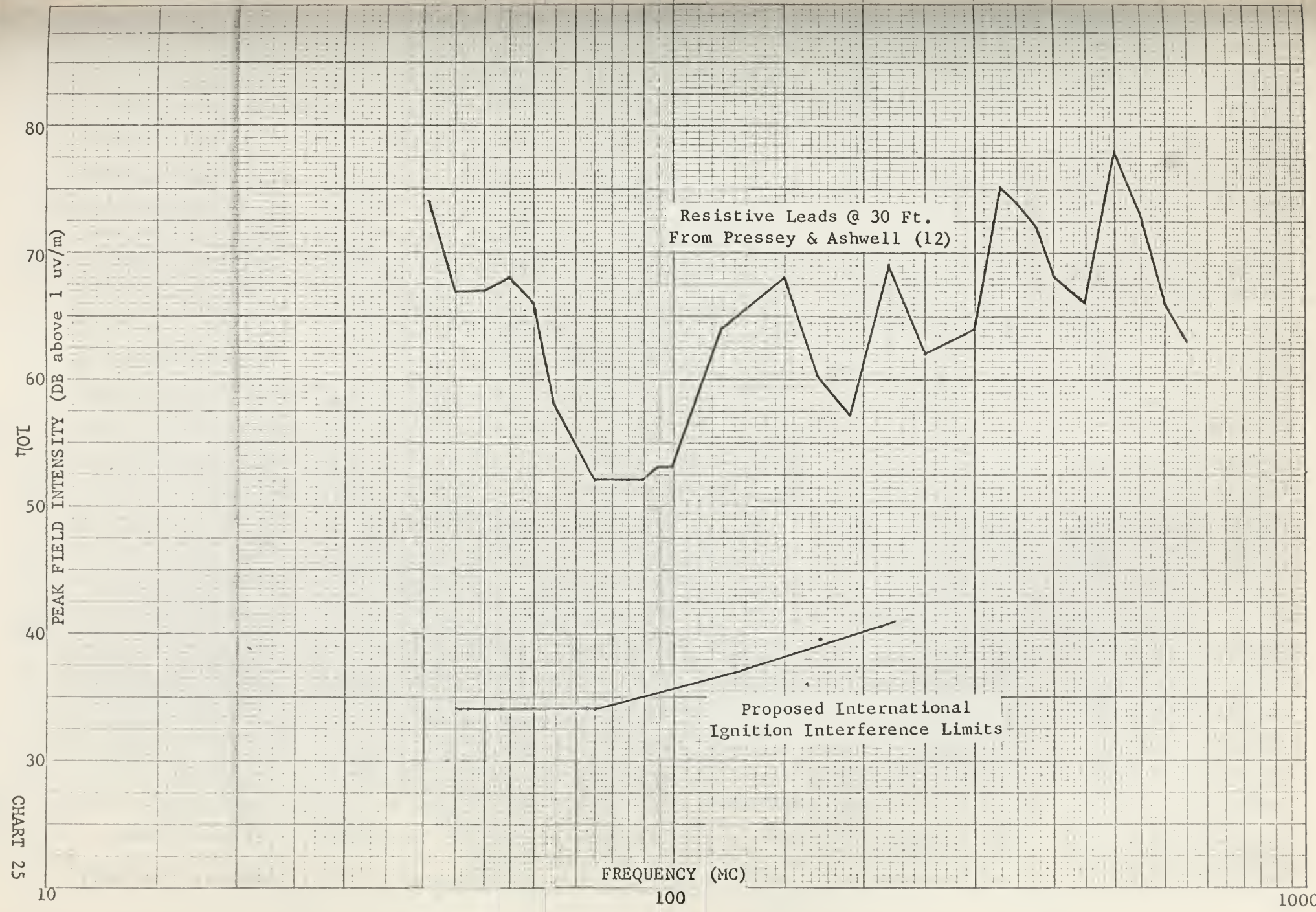
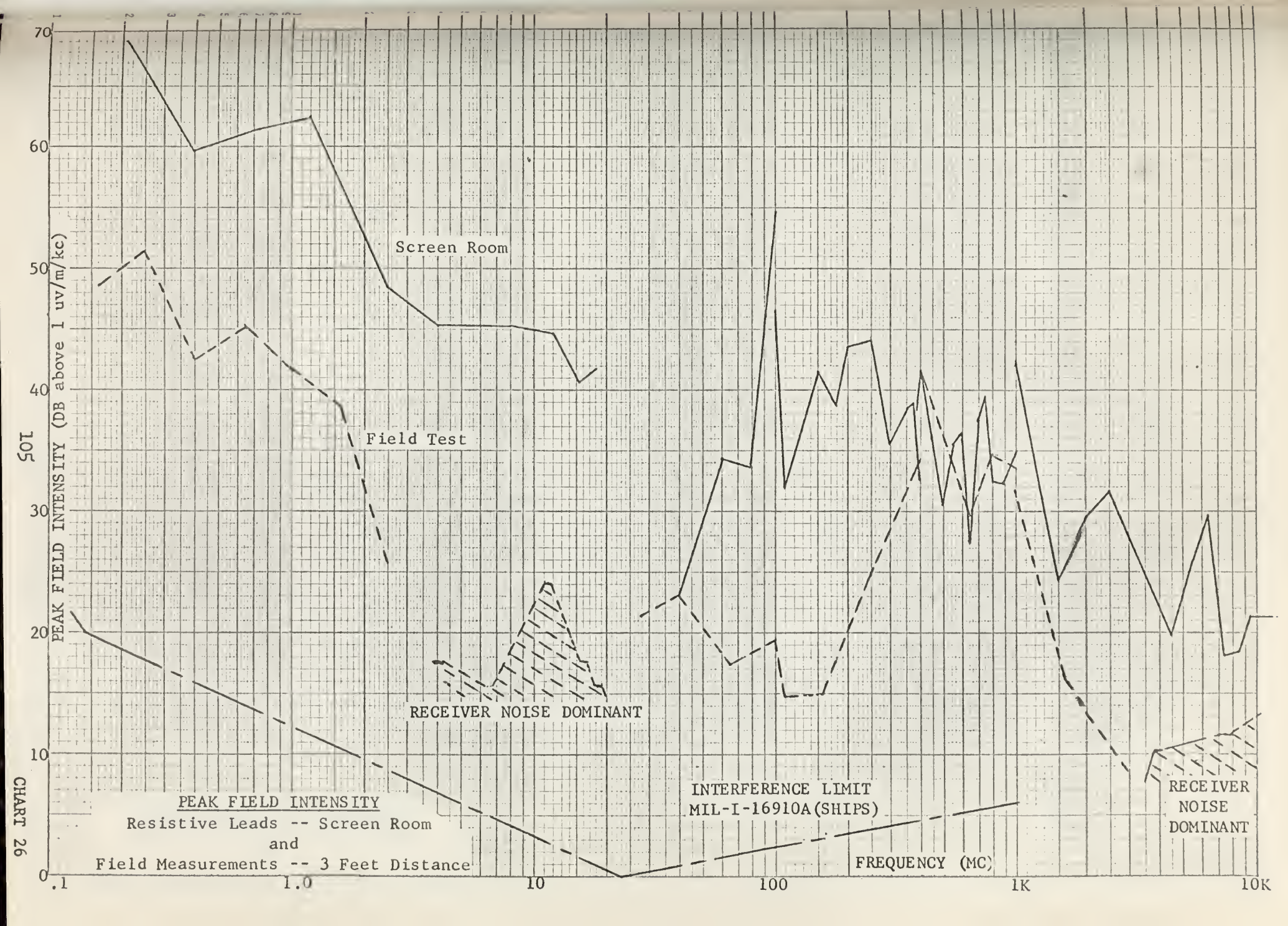
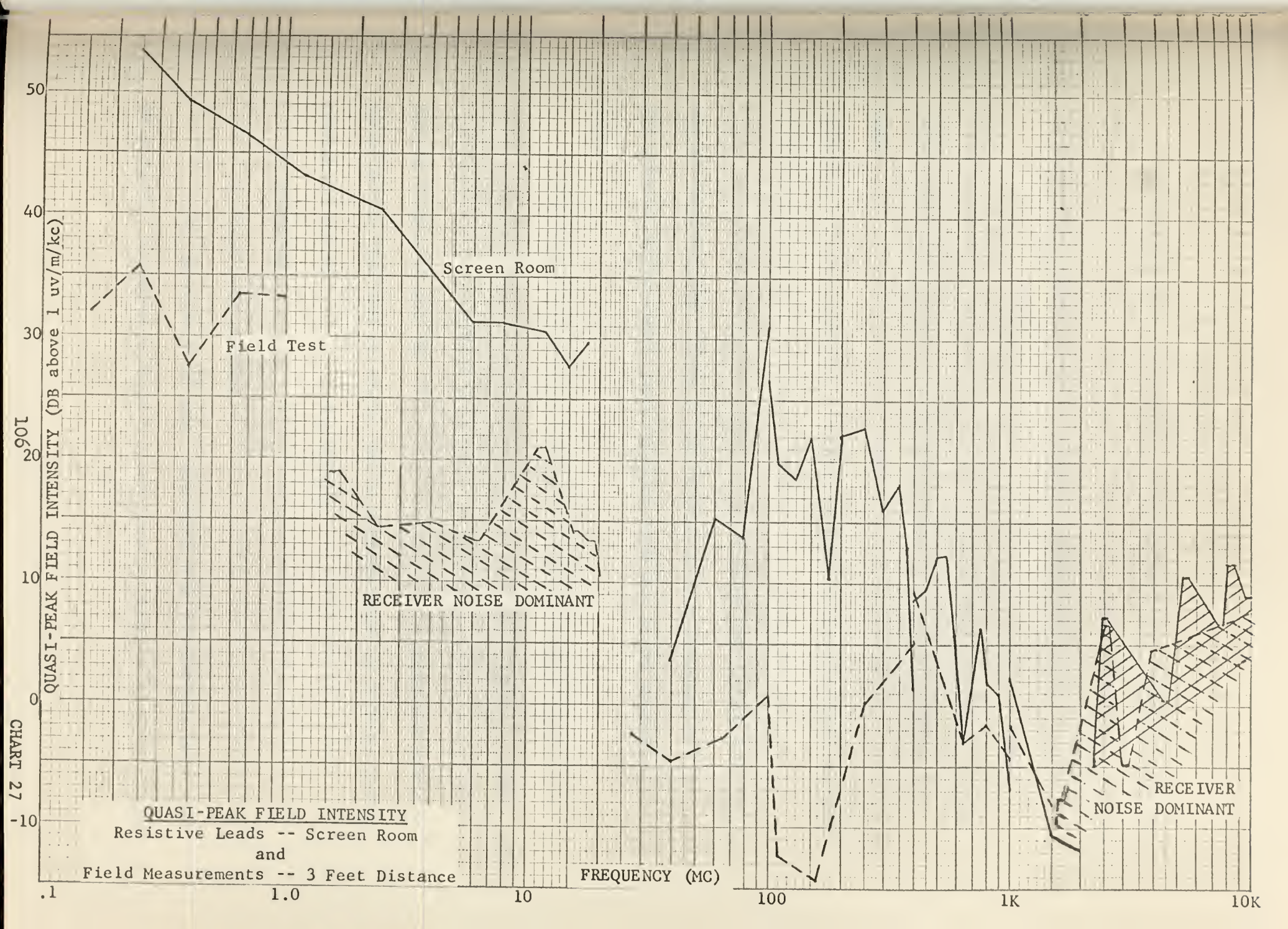

80
70
60
50
40
30
PEAK FIELD INTENSITY (DB above 1 uv/m)
Resistive Leads @ 30 Ft.
From Pressey & Ashwell (12)
Proposed International
Ignition Interference Limits
FREQUENCY (MC)
10
100
1000

CHART 25


70
60
50
40
30
20
10
0
PEAK FIELD INTENSITY (DB above 1 uv/m/kc)
105
Screen Room
Field Test
RECEIVER NOISE DOMINANT
INTERFERENCE LIMIT
MIL-I-16910A(SHIPS)
RECEIVER
NOISE
DOMINANT
PEAK FIELD INTENSITY
Resistive Leads -- Screen Room
and
Field Measurements -- 3 Feet Distance
FREQUENCY (MC)
.1
1.0
10
100
1K
10K
CHART 26



106

CHART 27

QUASI-PEAK FIELD INTENSITY

Resistive Leads -- Screen Room

and

Field Measurements -- 3 Feet Distance

9. Conclusions and Recommendations.

Conclusions from the previous sections have been summarized below. These include results of comparing field measurements with data published by other investigators and with proposed ignition interference limits.

1. Ignition interference has an extremely wide frequency spectrum. Screen room measurements with regular leads showed significant interference levels from 150 kc to 10 kmc (the range of measurements) for both quasi-peak and peak readings. Peak values of interference while using resistive leads were read from 150 kc to 10 kmc, while quasi-peak readings were obtained up to 2 kmc before "ambient" noise became predominant. Field measurements with the antenna located three feet distant from the car engine detected peak values of interference up to a frequency of 3 kmc; with the antenna 33 feet away, peak readings were lost in the ambient above 2.5 kmc.

2. The frequency spectrum displayed maxima at certain frequencies in each case and peak values were observed to vary quite rapidly. Screen room measurements gave definite indications of resonance effects in the ignition system (charts 13 and 15). Field measurements show prominent peaks at about 400 mc and 1000 mc which may be a combination of ignition system resonance and car body shielding effects.

3. Interference levels.

a. Field measurements -

(1) Antenna at 33 feet - Maximum peak interference level was 38 uv/m/kc. Interference drops to a low level at frequencies below 25 mc.

(2). Antenna at three feet - Maximum peak interference level was 41.7 uv/m/kc.

b. Screen room measurements -

(1). Above 10 mc the maximum peak interference level was 72 uv/m/kc for regular leads and 55 uv/m/kc for resistive leads. Below 10 mc the maximum interference level was approximately the same for both types of leads and was 73 uv/m/kc at 0.15 mc.

4. Measurements of interference levels with the antenna at 33 feet permit better reproducibility of data and minimize effects of the car body compared with measurements at three feet.

5. Above 20 mc resistive leads gave approximately a 20 db reduction of interference compared with regular leads.

6. Short resistive leads gave equal or high interference levels than the long resistive leads.

7. Above a certain minimum engine speed (about 700 rpm) there was no change in interference levels with further increase of speed.

8. Results from the spectrum analyzer show a 6 to 10 db variation in amplitude of radiation between spark plug firings. The variations were random in magnitude.

9. Waveform investigation showed discrete oscillatory frequencies up to approximately 30 mc. Limitations of the frequency response of the oscilloscope prevented measurements of higher oscillatory frequencies. These oscillatory frequencies were modulated by other frequency components giving complex waveforms.

10. Comparison of screen room measurements using resistive leads with field measurements at three feet illustrate the shielding effects of the car body (chart 26). Pressey and Ashwell stated in their paper (12) that the car body had little effect on interference levels while Egidi and Nano (18) stated that closing the car hood reduced interference by 18.6 db at 400 mc.

11. Field measurements above 200 mc gave interference levels higher than a linear extension of the proposed international ignition interference limits.

12. Ignition interference limits should cover the frequency range up to at least 1000 mc.

As discussed in Section 2 radio frequency interference has caused serious problems and imposed limitations on many electronic communication facilities. Programs for interference reduction have started in areas such as reducing susceptibility of electronic equipment, making compatibility studies of equipment and suppressing interference by various methods in equipment. Insufficient attention has been given to proper design and production of equipment to reduce interference at its source. Based on this premise and the above conclusions the following recommendations are made for ignition interference.

1. Additional measurements of ignition interference from American manufactured vehicles should be made. This would permit determination of statistical averages of radiation from various types of vehicles and then establishment of limits.

2. Ignition interference standards should specify 10 meters (33 feet) as the measurement distance.

3. Congressional or FCC action should be taken requiring that all new vehicles (cars, trucks, buses, etc.) manufactured meet the Ignition Interference limits.

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APPENDIX A

MIL-I-16910A (SHIPS) -- Applicable sections from Military Specification titled - "Interference Measurement, Radio, Methods and Limits: 14 Kilocycles to 1000 Megacycles "

Section 3.3 -- Standard units of Interference.

3.3.1 - Radiated - The standard unit of radiated broadband interference shall be microvolts per meter per kilocycle bandwidth, based on measurements made in open space, remote from any influence such as reflections, distortions, or disturbances which cannot be attributed directly to the sample under test. Continuous-wave (cw) type interference shall be in terms of microvolts per meter.

Section 3.4 -- Interference limits.

3.4.1 - Radiated interference limits - General limits of radiated interference in terms of the standard units are established and presented in graphic form on Figs. 7 and 8.

3.4.3 - Short Duration Interference

3.4.3.1 Impulse interference with a repetition rate of not more than 10 pulses per second is permitted, a limit of two times or 6 db above the limits shown on Figs. 7 and 8.

3.4.3.2 Interference of less than 1 second in duration occurring not more than once every 30 seconds is permitted a limit of 10 times or 20 db above the limits shown in Figs. 7 and 8.

3.4.3.3 Interference of less than 1 second in duration occurring not more than once during a time interval between 30 seconds and

and 3 minutes is permitted a limit of 30 times or 31.62 db above the limits shown on Figs. 7 and 8.

3.4.3.4 Interference of less than 1 second in duration occurring not more than once every 3 minutes shall be exempt from the requirements of this specification.

Section 6.3 -- Design - Radio interference should be carefully considered in the basic design of all equipment major units, assemblies, and systems. Electrical and electronic equipment should operate satisfactorily not only alone, but also in conjunction with other such equipment which may be placed nearby. This required that the operation of all such equipment should not be adversely affected by radio interference voltages and fields reaching it from external sources, and also requires that such equipment should not itself be of a source of radio interference which might adversely affect the operation of other nearby equipment. Therefore, design should be such that the least practical amount of radio interference is inherently generated and propagated before interference reduction major units are supplied. Such radio interference reduction major units and techniques that should be used, such as filtering, shielding and bonding, should be in conformance with good engineering practice and should be used efficiently in order to minimize space and weight penalties All possible advantages should be taken of the use of radio interference source reduction such as the use of mica capacitors directly at the interference sources.

Section 6.5 -- Measurement techniques in the presence of internal noise. - Internal noise is that energy present inherently in the input circuit

and which causes a meter indication with no radio frequency input in the measuring instruments specified in 6.1. This internal noise is caused by thermal agitation in the resistance of the input circuit and the tubes used in the first stages of the instrument. It has been determined that it is advantageous not to balance out the internal noise present in measuring instruments as the sensitivity of the instrument would be impaired. This internal noise has been taken into account in the limit curve shown on Fig. 7.

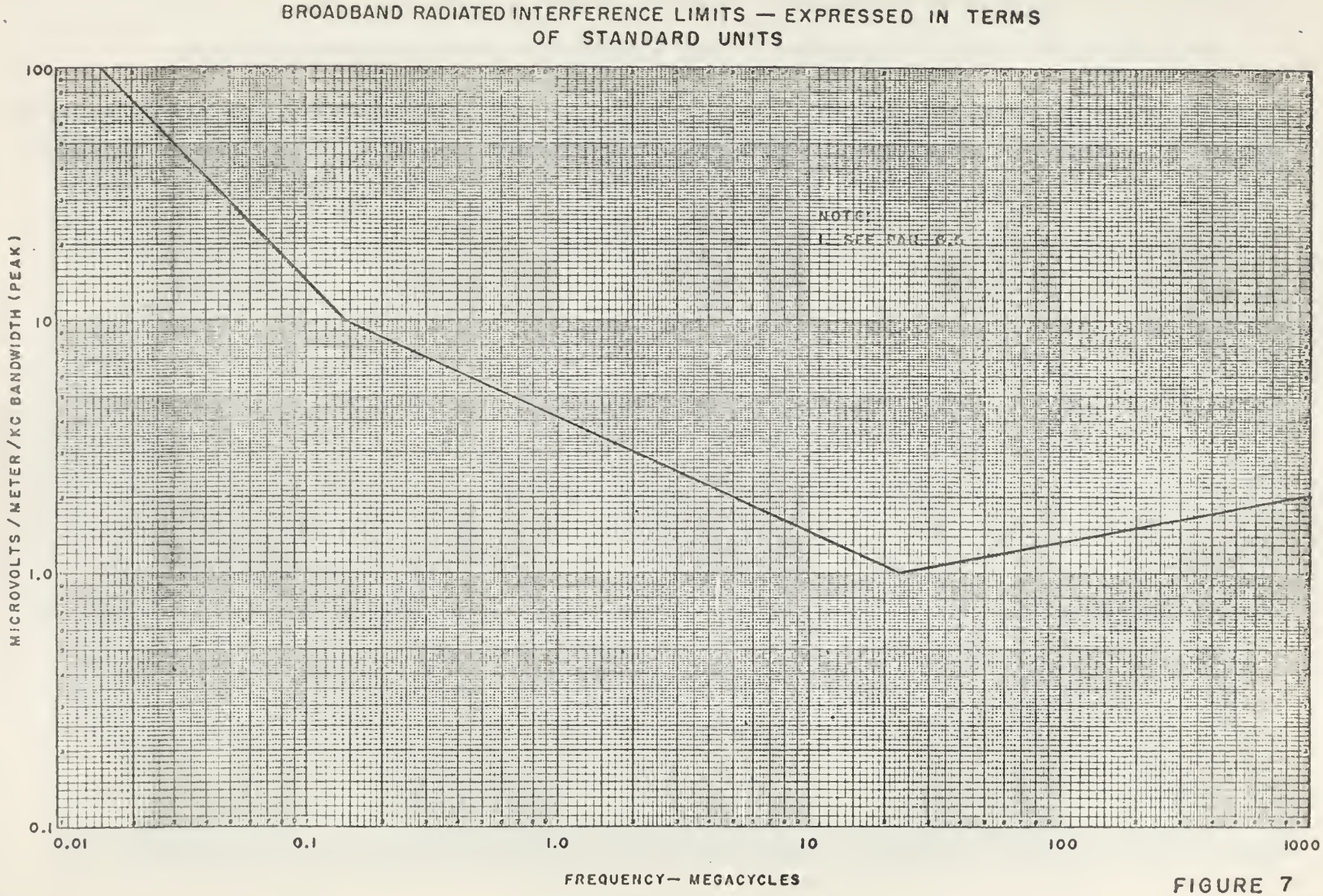


CHART 28

FIGURE 7
From MIL-I-16910A(SHIPS)

CHART 29

CW (SINE WAVE) RADIATED INTERFERENCE LIMITS - EXPRESSED IN TERMS OF STANDARD UNITS

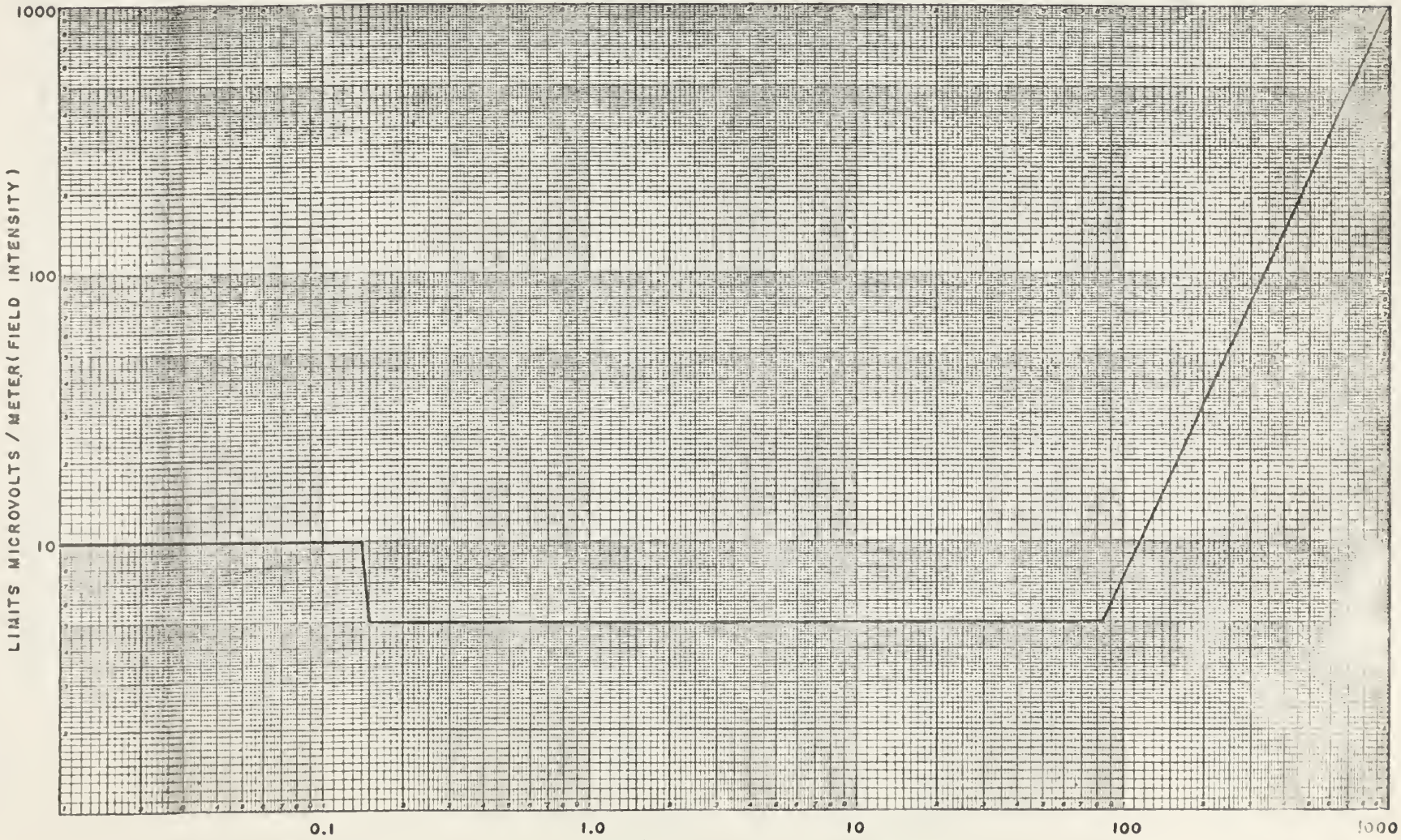


FIGURE 8
From MIL-I-16910A (SHIPS)

APPENDIX B

Draft International Standard for Measuring Ignition Interference, and Proposed Limits (18).

("Measuring Techniques for the Evaluation of the Interference Effect of Land Vehicles Moved by Combustion Engines with Electrical Ignition.")

1. Measuring Equipment (Including the Antenna)

The measuring equipment shall comply with the requirements laid down in the draft specification of CISPR: "Radio Interference Measuring Apparatus for the Frequencies 25 Mc/s to 300 Mc/s," Document CISPR (Central Office) 303.

2. General Conditions for Measurements

2.1 The measurements shall be performed at the following frequencies: 45, 65, 100, 125, 150, 175, 200, 225 Mc/s.

2.2 The horizontal component as well as the vertical component of the electric field shall be measured. For judgment of compliance with the limits stipulated in the graph of Fig. 10 (reproduced here as chart 30), the greater of the two values shall be taken into consideration.

2.3 The field strengths shall be measured with the electrical center of the dipole at a height of 2 meters above ground level. The dipole shall be directed towards the center of the engine.

2.4 The speed of the unloaded engine shall be increased during the test until the speed is reached which produces the greatest field strength.

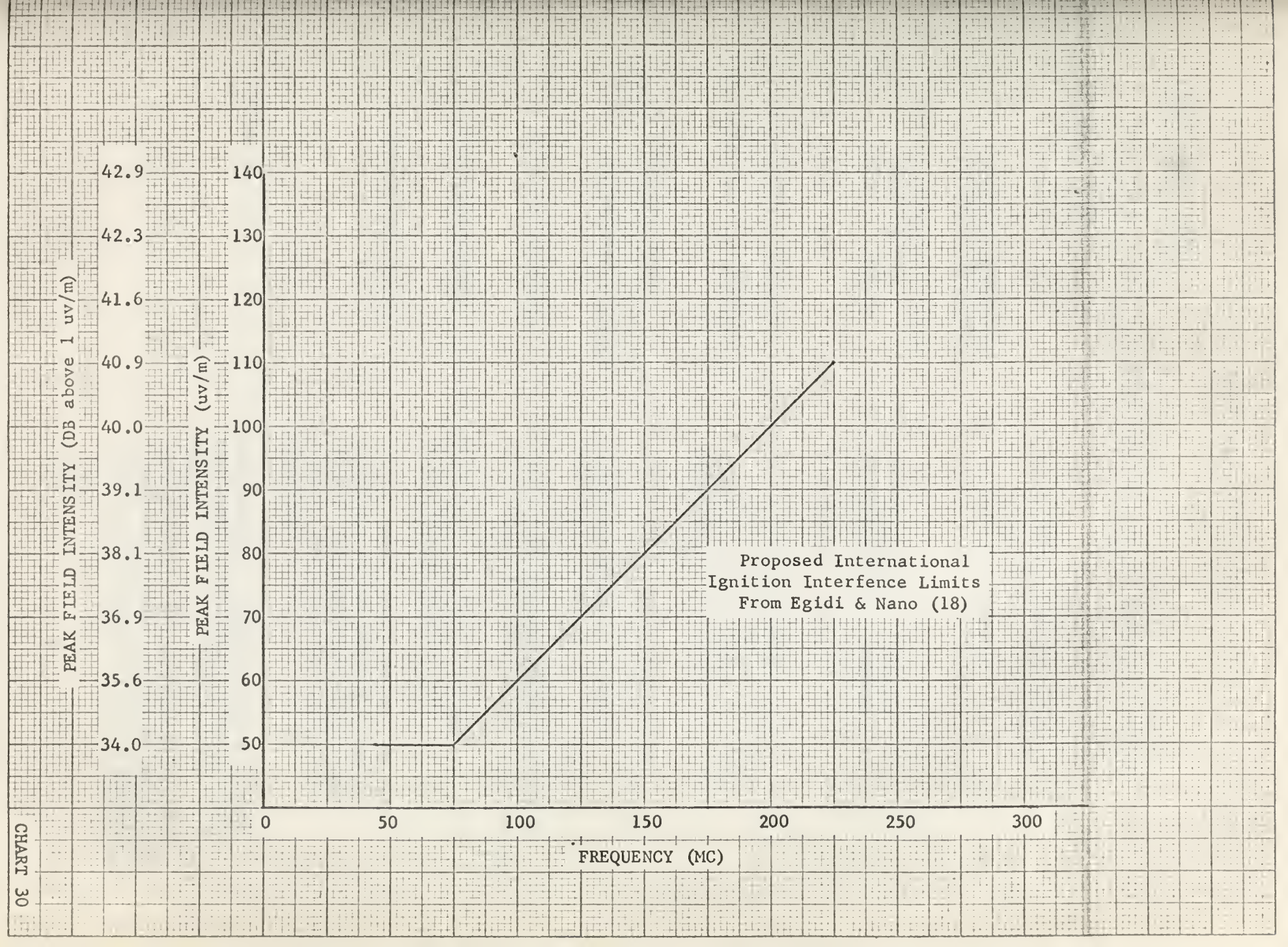
2.5 The width of the spark gap(s) of the spark plug(s) shall be adjusted according to the specification of the manufacturer for type testing. In all other cases, it shall remain in the condition as of the time of testing.

3. Miscellaneous Conditions for Measurements

3.1 Motor-cars.

3.1.2 During the measurements a driver shall be behind the wheel regulating the speed.

3.1.3 The measurements shall be made in four horizontal directions at a horizontal distance of 10 meters from the nearest metal part of the vehicle. To achieve that end, the antenna mast shall be placed at each of the four points situated at the stipulated distance on two straight lines intersecting at right angles at the center of the motor-car engine. One of the lines shall coincide with the longitudinal centerline of the car. The maximum of the four measured values will be utilized in determining whether the car under test complies with the limits stipulated in the graph of Fig. 10


PEAK FIELD INTENSITY (DB above 1 uv/m)
42.9
42.3
41.6
40.9
40.0
39.1
38.1
36.9
35.6
34.0
PEAK FIELD INTENSITY (uv/m)
140
130
120
110
100
90
80
70
60
50
Proposed International
Ignition Interfence Limits
From Egidi & Nano (18)
0
50
100
150
200
250
300
FREQUENCY (MC)
CHART 30

APPENDIX C

EQUIPMENT DATA:

1 Spectrum Analyzer -- Polarad Wide Dispersion Spectrum Analyzer, Model SA-84W

a. Frequency range --- 10 to 40,880 mc in nine bands

b. Resolution bandwidth (at the 3-db points) --- 2 to 80 kc, variable

c. Frequency dispersion ---
10 to 240 mc - - - --- 200 kc to 10 mc, variable
240 to 40,880 mc - - - --- 200 kc to 80 mc, variable

d. Sweep speed - - - --- 1 to 30 cps, variable

e. Crystal calibrators - - - --- 1, 10, 50, and 100 mc

2. Radio Test Set AN/PRM-1A --- Stoddart Aircraft Radio Co., Inc. Serial #71

a. Frequency range - - - --- 150 kc to 25 mc in seven bands

b. Intermediate Frequency --- 455 kc on bands 1, 3, and 4
1600 kc on bands 2, 5, 6, and 7

c. Effective bandwidth - - - --- Varies from approximately two to five kilocycles. See chart 31 for exact values

d. Input Attenuators - - - --- Five input attenuator settings X1, X10, X100, X1000, and X10,000

e. Quasi-peak circuit - - - --- In the quasi-peak position, the time constants of the detector weighting circuits are approximately one millisecond charge and 600 millisecond discharge

f. Antennas - - - - - - - --- Rod antenna - effective length of one-half meter and a physical length of 41 inches
Loop antenna - Rectangular shape with equivalent diameter of 8-1/4". Solenoid winding of 2 turns of 13 strand #36 wire.

3 Radio Test Set AN/URM-17 --- Stoddart Aircraft Radio Co., Inc. Serial #47

a. Frequency range ---------- 375 to 1000 mc in one band

b. Intermediate Frequency -------- 60 mc

c. Effective bandwidth ---------- Varies from approximately 0.75 to 1.16 mc. See chart 31 for exact values in db above 1 kc.

d. Input Attenuators ---------- X10, X100, $X10^3$, $X10^4$, and $X10^5$

e. Quasi-peak circuit ---------- In the quasi-peak position, the time constants of the detector weighting circuits are approximately one millisecond charge and 600 millisecond discharge.

f. Antenna ---------- Antenna is a dipole antenna that is tunable from 370 to 1000 mc. Consists of a base, a matching transformer section, and a dipole section.

4. Noise-Field Intensity Meter -------- Stoddart Aircraft Radio Co., Inc.
TS-587/U Serial #187 and #432

a. Frequency range ---------- 15 to 400 mc using a high frequency head from 100 to 400 mc and a low frequency head from 15 to 125 mc in three bands

b. Intermediate Frequency --------- 30 mc with the high frequency head
12 mc with the low frequency head

c. Effective bandwidth ---------- HF Approximately 185 kc
LF " 145 kc

d. Input Attenuators ---------- X1, X10, X100, and X1000

e. Quasi-peak circuit ---------- In the quasi-peak position, the time constants of the dectector weighting circuits are approximately two millisecond and 620 millisecond discharge

f. Antenna ---------- HF dipole antenna-tunable from 100 to 400 mc and a LF dipole antenna-tunable from 28 to 125 mc.

5. Radio Interference Measuring Set ---AN/URM-42 Stoddart Aircraft Radio Co., Inc.

a. Frequency range ----------1 to 10.75 kmc

b. Effective bandwidth ---------- Impulse noise bandwidth 1.57 mc and 6 db bandwidth 1.50 mc

c. Input Attenuators ----------X10, X100, $X10^3$, $X10^4$, $X10^5$

d. Quasi-peak circuit ---------- Time constants of the detector weighting circuits are approximately one millisecond charge and 600 millisecond discharge

e. Antenna ----------Small discone antenna - Used over the entire frequency range with the appropriate antenna factor

6. Cathode-Ray Oscilloscope -------- Type 555 - Tektronix, Inc.

a. Vertical-Deflection system - Used with a type 53B plug-in unit.

1. Frequency response - DC to 30 mc (3 db down)

2. Rise time - 0.017 microseconds for 0.05 to

0.2 volts/cm with DC coupling.

0.030 microseconds for 0.005 to

0.02 volts/cm with AC coupling.

b. Horizontal-Deflection system

1 Time Base range - 0.1 microseconds to 5 seconds per centimeter

in 24 calibrated steps.

2. Magnifier - Scale expands by factor of five. Fastest sweep speed

is 0.02 microseconds per centimeter ($\pm$ 5%)

c. Accelerating potential - 10 kilovolts

7. Signal Generator - Type HP 608C

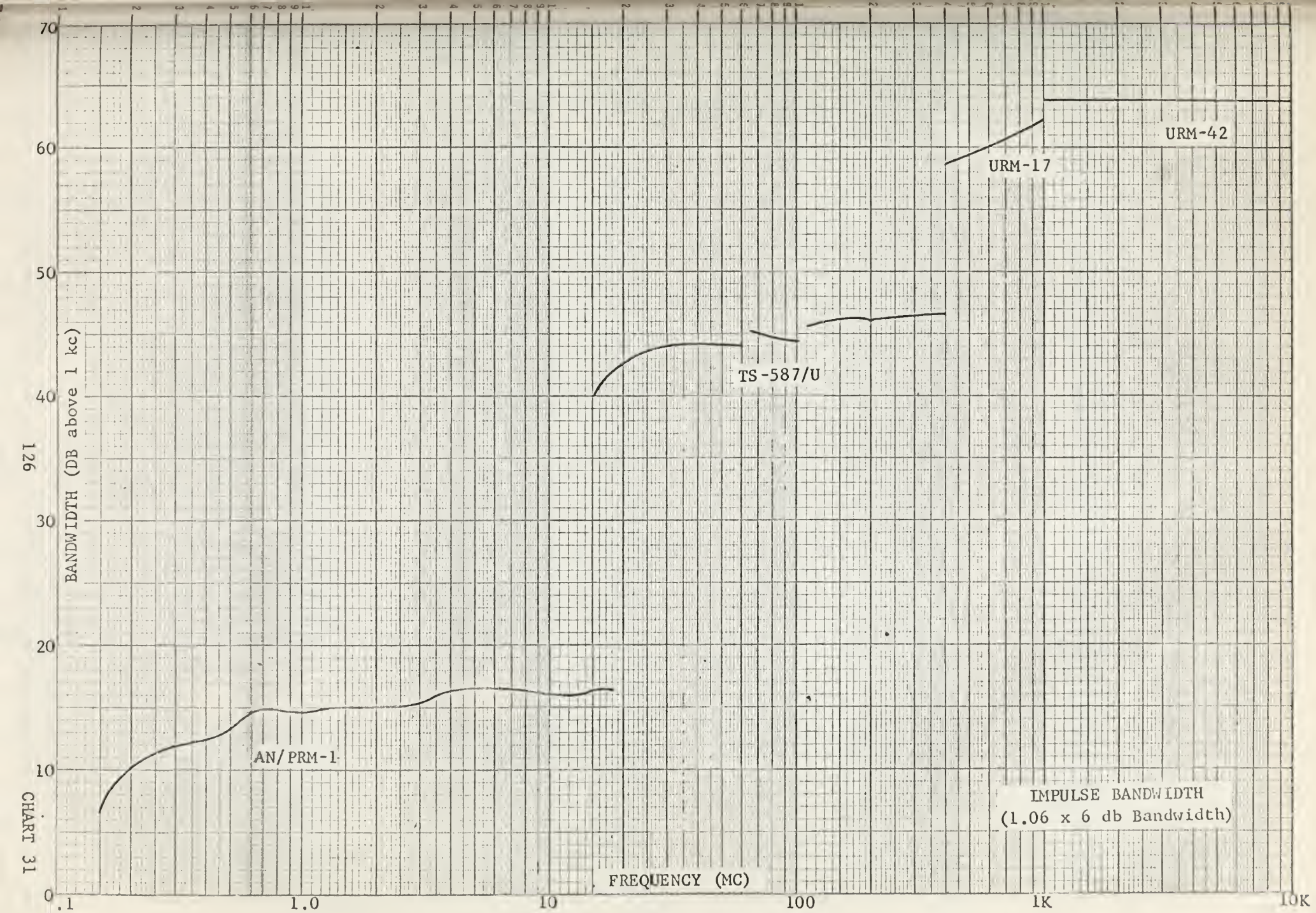
a. Frequency range ---------- 10 to 480 mc in five bands
Accuracy + 1%.

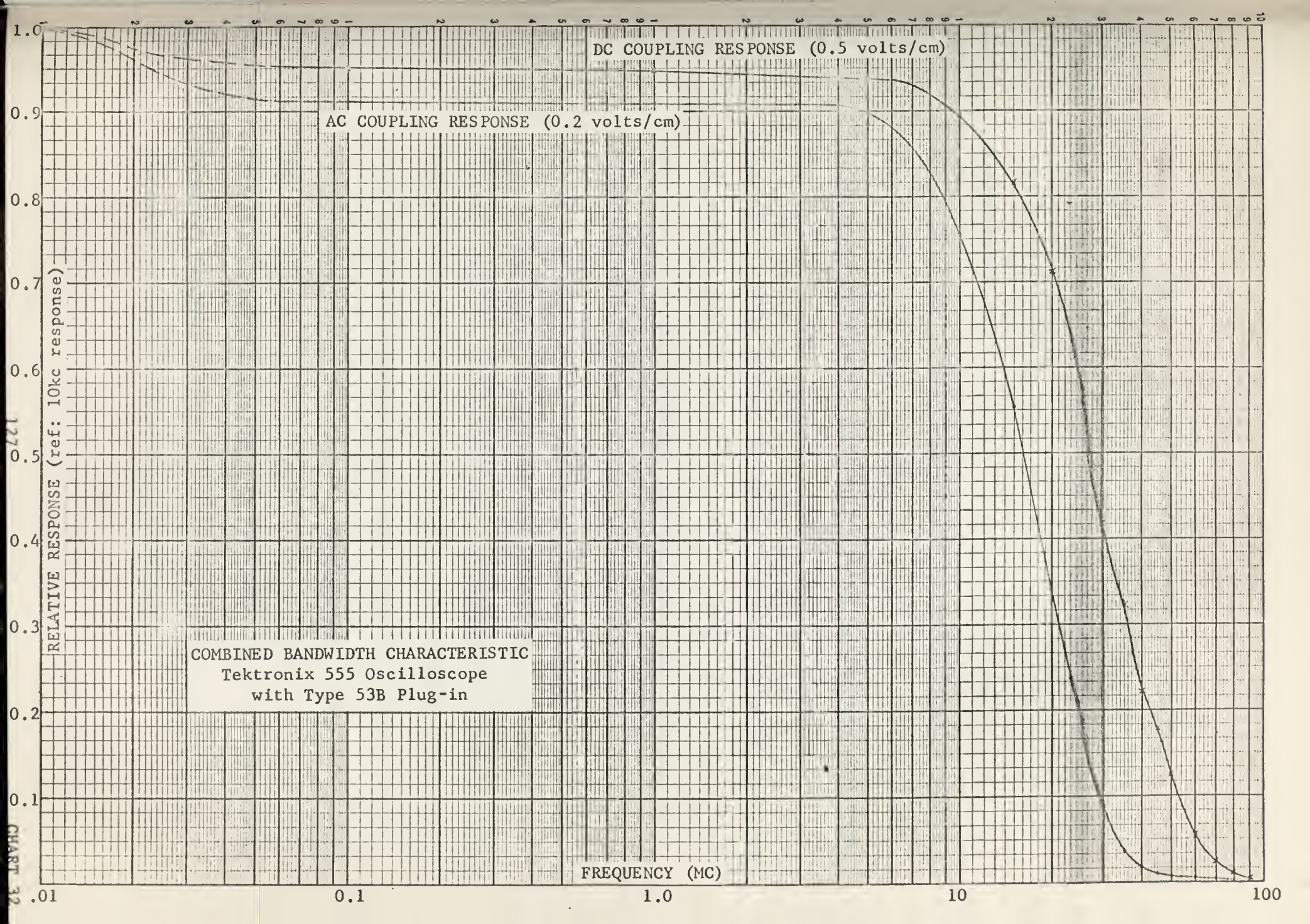
b. Output voltage ---------- Continuously adjustable from 0.1 uv minimum to 1 volt maximum when operated into 50 ohms.

8. Signal Generator - Type HP 612A

a. Frequency range ---------- 450 to 1230 mc in one band
Accuracy + 1%.

b. Output voltage ---------- 0.1 microvolts to 0.5 volts into 50 ohms. (+ 1%).


70
60
50
40
30
20
10
0
BANDWIDTH (DB above 1 kc)
126
CHART 31
URM-42
URM-17
TS-587/U
AN/PRM-1
IMPULSE BANDWIDTH
(1.06 x 6 db Bandwidth)
FREQUENCY (MC)
.1
1.0
10
100
1K
10K


DC COUPLING RESPONSE (0.5 volts/cm)
AC COUPLING RESPONSE (0.2 volts/cm)
RELATIVE RESPONSE (ref: 10kc response)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
COMBINED BANDWIDTH CHARACTERISTIC
Tektronix 555 Oscilloscope
with Type 53B Plug-in
FREQUENCY (MC)
.01
0.1
1.0
10
100

APPENDIX D

DEFINITIONS

1. Ambient interference - The interference level resulting from sources other than that being measured. This includes atmospherics, interference from man-made equipment and internal noise of the interference measuring set.
2. Arc - A low voltage, high-current discharge, as in contrast to a spark.
3. Atmospheric interference - Interference caused by the natural disturbances in the atmosphere. Produced principally by lightning discharges. Basically of the impulsive type and is the principal limitation at lower frequencies. Other sources are static discharges from snow, dust, rain and cosmic noise.
4. Bond - A low resistance element that joins two or more electrically conductive parts together.
5. Broadband noise - Noise extending over a wide range of frequencies, with the characteristics of periodic or aperiodic pulses of constant or random amplitudes. Broadband noise or interference is generated when the current flowing in a circuit is interrupted or established at a rate which departs radically from sinusoidal. Examples are some types of ambient noise, switching transients, ignition noise, power line noise, etc.
6. Continuous Wave (cw) interference - Interference having a narrow radio frequency spectrum. Examples are single frequencies radiating from electronic equipment such as oscillator harmonics.

7 Decoupling - Reduction or prevention of transfer of electrical interference from the source to the path of entry to the electronic device.

8 Effective bandwidth - The area under the frequency response curve divided by the peak height of the voltage curve For MIL-I-16910A the 6 db bandwidth is used. These are then modified depending on the type of interference Impulse bandwidth is 6 db band multiplied by 1.06.

9. Emission Spectrum - Power output at the terminals of a piece of equipment as a function of frequency.

10. Grounding - A process of electrically connecting parts and/or equipments to ground or earth potential.

11. Harmonics - An alternating quantity or wave motion of which the frequency is an odd or even multiple of a lower frequency called the fundamental frequency.

12. High-tension - Portion of the ignition system circuit between secondary of the coil and spark plugs. High voltages used to cause the spark discharge.

13. Impulse noise - Interference consisting of separate impulses which follow one another at such large time intervals that the transients produced in the receiver by one impulse have substantially died out by the time the next impulse arrives Intense bursts of energy of very short duration.

14. Incidental radiation - Any radiation from equipment other than the radiation necessary for the equipment to function

15. Interference - Undesired conducted or radiated electrical disturbances, including transients, within the range of frequencies covered by appli-

cable specifications, which may interfere with the operation of electronic equipment or communications.

16. Internal noise - A very low interference level originating in the circuitry of the interference measuring equipment, such as shot noise, thermal agitation, etc.

17. Low-tension - Primary side of the ignition coil. Low voltage portion of the ignition system.

18. Narrowband interference - Interference having a spectrum exhibiting one or more sharp peaks narrow in width compared to the nominal bandwidth of the interference measuring equipment. Example would be another transmitter in the same channel as the desired signal.

19. On-Off tests - Tests conducted to determine the source of interference by switching various equipment on and off while monitoring the interference.

20. Peak measurements - Interference measurements proportional to the peak amplitude of an interfering signal. It is usually the voltage required at the second detector to bring it to the threshold of audibility.

21. Quasi-peak measurements (QP) - Interference measurements proportional to the "nuisance" value of an interfering signal. Quasi-peaks provide a higher reading on impulsive interference than a field intensity reading. It can approach the field intensity reading for CW interference.

22. Radiated interference - Interference energy dispersed by radiation.

23. Radiation - The transfer of energy through a medium by electro-magnetic wave motion.

24. Random interference - Interference occurring at a random rate and at random levels. Spectral characteristics are the same as those that would be observed from a thermal noise source.

25. Resonance - The condition in an oscillatory circuit having its inductive reactance equal to its capacitive reactance at a certain frequency, at this point the current flow is a maximum.

26. Shielded enclosure - An area enclosed by shielding where the ambient interference is at a very low level, usually less than one microvolt per meter.

27. Spark - A high voltage, low current electrical discharge through a medium. Usually of very short duration.

28. Spectrum Analyzer - A radio receiver that provided a plot of a specified frequency range on a cathode-ray tube screen, portraying a graph of amplitude versus frequency.

29. Spurious emission - Emission of electromagnetic energy at any frequency or frequencies other than the designed operating frequency.

30. Spurious responses - A response of a receiver to any frequency or frequencies other than the one at which it is adjusted and designed to operate.

31. Suppression of interference - The reduction of interference effects by proper engineering techniques applied at the source, along the transmission path, or at the affected electronic equipment.

32. Susceptibility spectrum - Power required at the input terminals of a piece of equipment to produce threshold interference

33 Thermal noise - Thermal agitation of electrons in resistances which produce a voltage and thus noise signals.

34. Threshold interference - Amplitude of the interference signal required to produce a given percentage loss in intelligibility or desired output.

35. Transients - A disturbance of short time duration as opposed to steady state.

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